Valveless pumping and mixing enhancement in acoustically featured microchannels

Wang, Shasha

2012

Wang, S. (2012). Valveless pumping and mixing enhancement in acoustically featured microchannels. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/50669>

<https://doi.org/10.32657/10356/50669>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**VALVELESS PUMPING AND MIXING ENHANCEMENT
IN ACOUSTICALLY FEATURED MICROCHANNELS**

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SCHOOL OF MECHANICAL & AEROSPACE ENGINEERING

2012

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IN ACOUSTICALLY FEATURED MICROCHANNELS**

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School of Mechanical & Aerospace Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

2012

Abstract

The growing importance of microfluidics in life sciences and microengineering technologies leads to fast development of microfluidic devices. A generic microfluidic device can achieve many functions, among them fluid pumping and mixing are two basic functions. This thesis presents studies on a novel microfluidic chamber structure incorporated with piezoelectric actuations, which can be used for valveless micropumping and micromixing enhancement, depending on the actuation frequency. Both experimental investigation and numerical simulations are carried out to characterize the valveless micropumps and micromixers.

The valveless micropump in the present study mainly consists of a nozzle-shape channel that is formed by a planar channel with an acoustic resonator profile driven by a piezoelectric disk. There are two types of the design: one has buffer areas at the inlet and outlet and the other has no buffers. Both experimental measurements and numerical simulations are conducted to investigate the pumping characteristics of these pumps. The results show that the both types of pump work well at low frequencies, in terms of relatively high pressure heads and flowrates. The pumping direction for the pump with buffers at inlet/outlet is opposite to the pump without the buffers, while the peak pumping frequencies are the same for both pumps. The peak pumping frequency is found not to be caused by the piezoelectric disk, but probably by the acoustic feature of the actuation chamber, together with the connection channels. The numerical simulations, which simplify the three-dimensional flow in the pump into a two-dimensional flow problem, are conducted by using the software FLUENT. General agreements between the experimental measurements and the simulation results are obtained, in terms of pumping flowrates, the peak pumping frequency, and the pumping directions. Besides, the simulations provide transient flow patterns inside the pumping chambers, and the results show that the net flow pumping is due to flow rectification resulted from unsymmetrical flow fields in one pumping cycle. The unsymmetrical flow patterns in the micropumps are further confirmed qualitatively by synchronized PIV measurements.

The micromixer developed in the present study also has the acoustically featured microfluidic chamber and PZT actuation which are similar to that used in the valveless pumps. Experiments have been carried out to examine the mixing performance in DI water and DI water-glycerol solutions. The results show that at the actuation frequencies ranging from 1.0 kHz to 5.0 kHz, depending on the fluid viscosity, single (or multi-) bubble(s) can be generated in the channel near the actuation chamber. The interactions between bubble and acoustic field cause strong bubble oscillations, leading to significant mixing enhancement in the fluids, which would not occur otherwise. When the fluid viscosity is increased, the actuation frequency window becomes narrower and the bubbles are more difficult to be generated. The effective mixing enhancement has been achieved for the DI water-glycerol solutions with viscosity up to 44.75 mPa·s, which to our best knowledge is the highest viscosity of fluids in microfluidic mixing experiments.

Bubbles are observed in the micromixer at the proper actuation frequencies, and the bubble generation mechanism in this case has been further investigated. A numerical simulation is conducted to calculate the transient fluid pressure distributions inside the mixing chamber. The simulation results show that, corresponding to the actuations at the working frequency range used in the mixing experiment, low pressure regions are formed inside the microchamber, where the pressures are lower than the water vapor pressure in the working fluids, suggesting possible occurrence of bubbles. The bubble generations in the micromixer are verified experimentally by using a high speed camera. The captured images show that the bubbles are indeed generated around the low pressure regions predicted by the numerical simulations.

Acknowledgment

My deepest gratitude goes first and foremost to Associate Professor Huang Xiaoyang, my supervisor, for his excellent guidance, constructive suggestions, patient encouragement and continuous support during the past years of study and research. His expertise and experiences in acoustics and fluid dynamics never stop to amaze me.

I would like to thank Associate Professor Yang Chun, Charles, my co-supervisor, for his sincere encouragements, invaluable guidance, endless patience and support during the past years of research.

I also would like to thank Dr. John Chai Chee Kiong as my supervisor during the first semester. The literature training he created for me led me into the world of Ph. D research.

I would like to express my sincere appreciation to Dr. Jiao Zhenjun, who provides initial help for the experiments in this thesis. I thank lab technician staff Mr. Yuan Kee Hock, Mr. Cheo Hock Leong for the experimental supports. Special thanks to my fellow research students and staff in thermal and fluids lab, Yap Yit Fatt, Che Zhizhao, Li Haiwang, Patrick Tan, Foad Kabinejadian, Lewpiriyawong Nuttawut, Zhao Cunlu, Shen Yi, Liu Jing, Liu Guiqin, who helped me with useful discussions, suggestions and enriched my life with laughter and passion.

Last but not least, I would like to thank my beloved family for their encouragement, love and support.

Nomenclature

A_0	Maximum deflection at the centre of the piezoelectric disk, see Eq. (3.8) page 49
A_c	Coefficient, see Eq. (A.1) page 111
B	Magnetic field strength, see Eq. (2.2) page 17
B_c	Coefficient, see Eq. (A.1) page 111
C_c	Coefficient, Eq. (A.1) page 111
D_c	Coefficient, Eq. (A.1) page 111
E	Electric field, see Eq. (2.1) page 15
E_c	Coefficient, Eq. (A.1) page 111
F_d	Force density, see Eq. (2.1) page 15
F_L	Lorentz force, see Eq. (2.2) page 17
$F_{\bar{V}}$	The body force, see Eq. (3.9) page 49
f	Frequency, see Eq. (3.8) page 49
h	Constant pump thickness, see Eq. (3.3) page 48
I	Electric current, see Eq. (2.2) page 17
$\bar{I}_{0i}$	Normalized minimum intensity at each point, see Eq. (4.2) page 81
I_i	Image intensity, see Eq. (4.2) page 81
$\bar{I}_i$	Normalized intensity at each point, see Eq. (4.2) page 81
$\bar{I}_{\infty}$	Normalized maximum intensity, see Eq. (4.2) page 81
N	The total number of points examined, see Eq. (4.2) page 81

Nomenclature

n	Number of substreams
P	Polarization vector, see Eq. (2.1) page 15
Pe	Peclet number
Δp	Pressure difference
Δp_{crit}	Critical pressure difference
p	Pressure, See Eq. (3.2) page 48
$\Delta p_{\text{water-vapor}}$	Water vapor pressure
q_f	Free space-charge density, see Eq. (2.1) page 15
R	Radius of the circle in pump chamber, see Eq. (3.8) page 49
R_0	Radius of bubble
Re	Reynolds number
r	Distance to the centre of chamber, see Eq. (3.8) page 49
St	Strouhal number
T	Period of one pumping cycle
t	Time
u	Velocity, see Eq. (4.1) page 78
$\bar{V}$	Fluid velocity with x, y directions, see Eq. (3.3) page 48
V	Fluid velocity in three-dimensional with x, y , and z directions, see Eq. (3.2) page 48
w	Distance between the electrode, see Eq. (2.2) page 17
x, y, z	Coordinates

Greek letters

α	Damping coefficient, see Eq. (3.6) page 48
$\bar{\alpha}$	Time averaged value damping coefficient, see Eq. (A.3) page 112
β	Non-linear coefficient, see Eq. (3.6) page 48
$\bar{\beta}$	Time averaged value non-linear coefficient, see Eq. (A.4) page 112
ε	Fluid permittivity, see Eq. (2.1) page 15
ζ	Oscillation displacement of the piezoelectric disk, see Eq. (3.3) page 48
λ	Wavelength
μ	Dynamic viscosity, see Eq. (4.1) page 78
ν	Kinematic viscosity, see Eq. (3.2) page 48
ρ	Density
σ	Mixing efficiency, see Eq. (4.1) page 78

Abbreviations

2ddp	Two-dimensional double precision
CFD	Computational fluid dynamics
DNA	Deoxyribonucleic acid
DI water	De-ionized water
EHD	Electrohydrodynamic
FEA	Finite element analysis
LED	Light emitting diode
LOC	Lab on a chip
MEMS	Microelectromechanical systems
MHD	Magnetohydrodynamic

Nomenclature

NS	Navier-Stokes
PCB	Printed circuit board
PCR	Polymerase chain reaction
PDMS	Polydimethylsiloxane
PIV	Particle image velocimetry
PMMA	Polymethylmethacrylate
PZT	PbZrTiO ₃ lead-zirconate-titanate
SEM	Scanning electron microscope
SHM	Staggered herringbone mixer
TTL	Transistor-Transistor Logic
UDF	User-defined-function

Contents

Abstract.....	I
Acknowledgment.....	III
Nomenclature	IV
Contents	VIII
List of Figures.....	XII
List of Tables	XXIII
Chapter 1 Introduction.....	1
1.1 Background.....	1
1.2 Objectives	2
1.3 Outline of the Thesis.....	3
Chapter 2 Literature Review	5
2.1 Introduction.....	5
2.2 Mechanical Micropumps	6
2.2.1 Check-valve Pumps	7
2.2.2 Peristaltic Pumps.....	9
2.2.3 Valveless Rectification Pumps	10
2.3 Nonmechanical Micropumps	15
2.3.1 Electrohydrodynamic Pumps	15
2.3.2 Electrokinetic Pumps	16
2.3.3 Magnetohydrodynamic Pumps	17
2.4 Passive Micromixers.....	17
2.4.1 Lamination Mixers.....	17

2.4.2 Chaotic Mixers	18
2.4.3 Droplet Mixers	20
2.5 Active Micromixers	21
2.5.1 Pressure Driven Mixers.....	21
2.5.2 Electrokinetic Mixers.....	21
2.5.3 Acoustically Actuated Mixers.....	22
2.5.4 Magnetohydrodynamic Mixers	24
2.6 PIV Measurement	25
2.7 Bubble Generation in the Microchannel	26
Chapter 3 Valveless Micropumps with Acoustically Featured Microfluidic Chambers.....	28
3.1 Introduction.....	28
3.2 Experiments	29
3.2.1 Device Design and Fabrication	29
3.2.2 Experimental Setup and Measurement	32
3.2.2.1 Pump pressure measurement.....	33
3.2.2.2 Flow rate measurement	35
3.2.2.3 Disk deflection measurement.....	36
3.2.3 Experimental Results and Discussions	37
3.2.3.1 Flow rate and Pressure head.....	37
3.2.3.2 Disk deflection and pumping flow rate.....	41
3.3 Numerical Simulations	46
3.3.1 Problem Description and Assumptions.....	47
3.3.2 Governing Equations.....	47
3.3.3 Mesh Constructions and Independent Analysis.....	50
3.3.4 Simulation Results and Comparison with Experiments.....	53

3.3.4.1 Pumping direction and flow patterns	53
3.3.4.2 Comparisons between the simulations and experiments.....	59
3.3.4.3 Effect of channel configuration.....	62
3.4 PIV Measurements of Flow Patterns in the Micropump	64
3.4.1 Experimental Setup	64
3.4.2 PIV Results and Comparison with Simulation Results.....	68
3.5 Summary	72
Chapter 4 Mixing Enhancement in Microchannels with Oscillating Bubbles	73
4.1 Introduction.....	73
4.2 Micromixer Design, Fabrication and Experimental Setup	74
4.2.1 Micromixer Design and Fabrication	74
4.2.2 Experimental Setup and Measurement	76
4.3 Mixing Enhancement in for DI Water	78
4.3.1 Experimental Observation on Mixing.....	78
4.3.2 Efficiency of Mixing	81
4.3.3 Effect of Disk Vibrations	83
4.4 Mixing Enhancement for High Viscous Fluids	84
4.4.1 High Viscous Mixing Fluids and Experimental Preparation	84
4.4.2 Mixing for High Viscous Fluids and Effects of Fluid Viscosity	86
4.4.3 Effects of the Flow Rate.....	91
4.5 Experiments of a Straight Channel Mixer: No Mixing and No Bubbles.....	92
4.6 Summary	96
Chapter 5 Bubble Generation in the Microfluidic Chamber.....	97
5.1 Introduction.....	97
5.2 Numerical Simulation of Pressure Distribution in Micromixer.....	97
5.2.1 Numerical Results for DI Water	98

5.2.2 Numerical Results for High Viscous Fluids	101
5.3 Bubble Generation Observation.....	104
5.3.1 Experimental Setup	104
5.3.2 Experimental Results and Discussion	105
5.4 Summary	107
Chapter 6 Conclusions and Recommendations.....	108
6.1 Conclusions.....	108
6.2 Recommendations for Future Work	110
Appendix A	111
A.1 Damping Coefficient α and Non-linear Coefficient β	111
A.2 Temperature of PZT Disk in the Experiments	112
Publication List	116
References	117

List of Figures

Fig. 2.1 Schematic of the external actuators used in microflow control devices. (a) Electromagnetic; (b) Piezoelectric bimorph (Disk Type); (c) Piezoelectric bimorph (Cantilever Type); (d) Piezoelectric stack; (e) Pneumatic; (f) Shape memory alloy and bias spring. [14].....	6
Fig. 2.2 Schematic of the micromachinable actuators used in microflow control devices. (a) Electrostatic actuator; (b) Thermopneumatic actuator; (c) Electromagnetic actuator; (d) Bimetallic actuator. [14].....	7
Fig. 2.3 Principle construction of a mechanical micropump and check valves [2].	8
Fig. 2.4 Micro diaphragm pumps with piezoelectric actuation and passive membrane valves. (a) Two-valve pump; (b) Three-valve pump. [15].....	8
Fig. 2.5 Peristaltic micropump: schematic representation of the valve actuation scheme for pumping from inlet to outlet (top to bottom). [17].....	9
Fig. 2.6 Schematic pumping principle diffuser/nozzle valveless micropump. (a) Supply mode; (b) Pump mode. [18]	10
Fig. 2.7 Valveless rectification micropump with piezoelectric actuation. [18]	11
Fig. 2.8 Valveless planar micropump: top and bottom view. [19]	12
Fig. 2.9 SEM photos of a diffuser element. (a) Etched isotropically; and (b) Etched depth of 80 μm . [20]	12
Fig. 2.10 Simulated velocity field inside the diffuser/nozzle pump in (a) Supply mode; (b) Pump mode. [24]	13
Fig. 2.11 The valveless micropump with dynamic passive valves. [35, 36]	15
Fig. 2.12 (a)Valvular conduit pump; (b) The tesla valve. [37]	15

Fig. 2.13 Staggered herringbone mixer (SHM). (a) Schematic diagram of one-and-a-half cycles of the SHM; (b) Confocal micrographs of vertical cross sections of a channel as in (a). [62].....	19
Fig. 2.14 Micromixer designs for mixing with chaotic advection [10]. (a) Slanted ribs; (b) Slanted grooves [62, 63]; (c) Staggered-herringbone grooves [62, 63]; (d)(e)(f) Patterns for surface modification in a micromixer with electrokinetic flows [65]; (g) Modified Tesla structure; (h) C-shape [66]; (i) L-shape [67]; (j) Connected out-of-plane L-shape [68]; (k) Twisted microchannel [69]; (l)(m)(n) Other designs of twisted channel [70]; (o) Obstacles on wall [71]; (p) Obstacles in the channel [64]; (q) A zig-zag-shaped channel [72].	19
Fig. 2.15 Schematic drawing of the cross section of the mixing chamber in an ultrasonic micromixer. [107, 108].....	23
Fig. 2.16 Schematic drawing of air pockets on the inner wall of the mixing chamber of bubble-induced acoustic micromixer. [109, 110]	23
Fig. 3.1 Schematics of the planar valveless pump.	29
Fig. 3.2 Stacked concepts of the micropumps. (a) Pump without buffer; and (b) Pump with buffers.	30
Fig. 3.3 Photograph of a piezoelectric disk.....	30
Fig. 3.4 Geometry of the pump with acoustically featured chamber. (a) Pump without buffer and (b) pump with buffers.	31
Fig. 3.5 Assembled micropump with buffers. The bottom photo of the micropump is filled with fluorescent dye solution, which is only for clear description of the pump chamber with buffers.....	32
Fig. 3.6 Experiment setup for pressure head measurement.	34
Fig. 3.7 Pressure measurement for (a) Pump without buffer; (b) Pump with buffers. .	34

Fig. 3.8 Schematics and photos of experiment set up for flow rate measurement.	35
Fig. 3.9 Photograph of the measurement of disk deflection, (a) Micropump; (b) ADE Microsense II Probe; (c) ADE Microsense II OEM Gauging Module, which is used to control distance between the probe and the PZT disk in an effective range by too near or too far lamp.	37
Fig. 3.10 Flow rate and pressure head versus frequency at voltage 60 V for the pump with buffers.	38
Fig. 3.11 Flow rate and pressure head versus frequency at voltage 150 V for the pump with buffers.	38
Fig. 3.12 Flow rate and pressure head versus frequency at frequency 70 Hz for the pump with buffers.	39
Fig. 3.13 Flow rate and pressure head versus frequency at voltage 60 V for the pump without buffer.	40
Fig. 3.14 Flow rate versus voltage at frequency 70 Hz for the pump without buffer. ...	40
Fig. 3.15 Measurement results of the actuation disk for the pump with buffers. (a) Disk deflection versus frequency and (b) Disk deflection versus voltage. ...	42
Fig. 3.16 Measurement results of the actuation disk for the pump without buffers. (a) Disk deflection versus frequency and (b) Disk deflection versus voltage. ...	43
Fig. 3.17 Flow rate, disk deflection, and disk velocity versus frequency at voltage of 60 V for the pump with buffers.	44
Fig. 3.18 Flow rate, disk deflection, and disk velocity versus frequency at voltage of 150 V for the pump with buffers.	45
Fig. 3.19 Flow rate, disk deflection, and disk velocity versus frequency at voltage of 60 V for the pump without buffer.	45

Fig. 3.20 Flow rate, disk deflection, and disk velocity versus frequency at voltage of 150 V for the pump without buffer.....	46
Fig. 3.21 Sketch of mesh constructions of (a) Pump with buffers; (b) Pump without buffer; (c) The junction between the chamber and channels in pumps; (d) The junction between the buffers and channels in the pump with buffers...	50
Fig. 3.22 Mesh independent analysis of the pressure on the center line at $t = T/2$ (T is the period), frequency 70 Hz, voltage 60 V for the pump with buffers.....	52
Fig. 3.23 The flow rates for different levels of mesh for the case at frequency of 70 Hz and voltage of 60 V for the pump with buffers.	52
Fig. 3.24 The pumping flowrates in one pumping cycle for two pumps working at the driving frequency of 70 Hz and voltage of 60 V. (a) The pump with buffers and (b) The pump without buffer. T is the pumping period.....	53
Fig. 3.25 Flow streamlines at frequency of 70 Hz and voltage of 60 V for pump with buffers (a) $t = T/4$ when the disk reaches to the up-most position; (b) $t = T/2$ when the disk moving down in the middle position; (c) $t = 3T/4$ when the disk reaches to the bottom-most position; (d) $t = T$ when the disk moving up in the middle position.....	55
Fig. 3.26 (a) Detailed flow streamlines inside the dashed rectangular indicate in Fig. 3.25(a) at $t = T/4$, and (b) detailed flow streamlines inside the dashed rectangular indicate in Fig. 3.25(c) at $t = 3T/4$. The pump with buffers is actuated at 70Hz and 60V.	56
Fig. 3.27 Flow streamlines at frequency of 70 Hz and voltage of 60 V for the pump without buffers (a) $t = T/4$ when the disk reaches to the up-most position; (b) $t = T/2$ when the disk moving down in the middle position; (c) $t = 3T/4$	

when the disk reaches to the bottom-most position; (d) $t = T$ when the disk moving up in the middle position.....	57
Fig. 3.28 (a) Detailed flow streamlines inside the dashed rectangular indicate in Fig. 3.27(a) at $t = T/4$ and (b) detailed flow streamlines inside the dashed rectangular indicate in Fig. 3.27(c) at $t = 3T/4$. The pump without buffers is actuated at 70Hz and 60V.	58
Fig. 3.29 Detailed flow streamlines in numerical simulations inside dashed rectangular areas at $t = T/8, t = 2T/8, t = 3T/8, t = 4T/8, t = 5T/8, t = 6T/8, t = 7T/8, t = 8T/8$. The pump with buffers is driven at frequency of 500 Hz and voltage of 210 V. There is no pumping effect in this case according to experiments.	58
Fig. 3.30 Experiment and simulation of flow rate versus frequency at voltage of 60 V for the pump with buffers. The experimental error is about 2.5%.....	59
Fig. 3.31 Experiment and simulation of flow rate versus frequency at voltage of 150 V for the pump with buffers. The experimental error is about 2.5%.....	60
Fig. 3.32 Experiment and simulation of flow rate versus frequency at frequency of 70 Hz for the pump with buffers. The experimental error is about 2.5%.	60
Fig. 3.33 Experiment and simulation of flow rate versus frequency at voltage of 60 V for the pump without buffer. The experimental error is about 2.5%.	61
Fig. 3.34 Experiment and simulation of flow rate versus frequency at frequency of 70 Hz for the pump without buffer. The experimental error is about 2.5%.....	61
Fig. 3.35 Variation of flow rates of different geometry micropumps with buffers.	63
Fig. 3.36 Variation of flow rates of different geometry micropumps without buffer...	63
Fig. 3.37 Experimental setup of PIV measurement. The two-channel signal generator provided driving voltage and phase trigger signals to both voltage amplifier	

and laser, respectively. Micropump was fixed on a shelf and actuated by the voltage amplifier. The actions of laser and micropump were assigned synchronized by external triggered signal from a two-channel generator. ...65	
Fig. 3.38 Photograph of PIV experimental setup.....65	
Fig. 3.39 The measurement zone I and zone II indicated by the dashed rectangulars in the micropump with buffers.66	
Fig. 3.40 Timing diagram of the PIV measurement (not to scale).67	
Fig. 3.41 Pumping cycle and eight moments corresponding to the piezoelectric disk positions moving up and down. The pumping phase starts at $2T/8$ when the disk reaches to the up-most position and is then moving down to the mid-position at $3T/8$. At $t = 4T/8$ the disk is in the mid-position and continuously moving down from the mid-position at $5T/8$ to pump the fluid out of the chamber. The sucking phase (lower row) starts at $6T/8$ when the disk reaches to the bottom-most position and is moving up from the bottom through $7T/8$ and T till $T/8$ in next cycle.68	
Fig. 3.42 Flow velocity patterns inside the pump chamber (zone I indicated in Fig. 3.39) at eight moments in one pumping period T . The left column from $2T/8$ to $5T/8$ is the pumping phase, while the right column is the sucking phase. The pump was actuated at 70Hz and the period T is 0.0143 s.....69	
Fig. 3.43 Detailed PIV flow patterns (in zone II) corresponding to the flow velocity fields at 8 moments shown in Fig. 3.39. The upper row is the pumping phase and the lower row is the sucking phase. The pump was actuated at 70Hz and the period T is 0.0143 s.....71	
Fig. 3.44 Numerical simulations of the flow streamlines inside zone II (indicated in Fig. 3.39). The upper row shows the pumping phase from $t = 2T/8$ to $5T/8$.	

The lower row shows the sucking phase starting from $6T/8$, through $7T/8$ and T , to $T/8$ in next cycle. The pump was actuated at 70Hz and the period T is 0.0143 s.	71
Fig. 4.1 Schematic illustration of the acoustic micromixer. (a) Side view of the mixer configuration; (b) Top view of the mixer.....	74
Fig. 4.2 Stacked concept of the micromixer.	75
Fig. 4.3 Assembled micromixer.....	76
Fig. 4.4 Experiment setup of micromixer.	77
Fig. 4.5 Visualization of fluorescent dye in mixing experiment before powering on the piezoelectric disk.....	78
Fig. 4.6 Visualization and intensity distribution of fluorescent dye in the mixer for various applied frequencies. The experimental images (left) used for assessing mixing quality are taken from the region indicated by the dashed-line rectangle in Fig. 4.5. Arrows show the location of acoustically induced gas bubbles. The fluorescent intensity distribution (right) are obtained by digitized the fluorescent images along the cross-section, a-a shown in Fig. 4.1(b).	80
Fig. 4.7 The actuation induced bubbles at 1 kHz applied frequency are still in the channel when the power is switched off, but the mixing enhancement phenomenon is disappeared.	81
Fig. 4.8 Variation of the mixing efficiency with applied frequency.....	82
Fig. 4.9 Vibrating velocity of the piezoelectric disk versus various applied frequency.	83
Fig. 4.10 A picture of the mixing device used in the study. The image shows that in the absence of generated bubbles before actuating the piezoelectric disk and no	

	mixing in the fluid. DI water-glycerol solution supplied from inlet A and a DI water-glycerol solution with fluorescent dye supplied from inlet B. The cross line C-C is chosen to analyze the mixing efficiency.....	85
Fig. 4.11	Effect of the actuation frequency on mixing of a fluorescent dye in the DI water-glycerol solution with a viscosity of 5.69 mPa·s. The actuation frequency was varied from 0.5 kHz to 3.5 kHz. The applied voltage and the flowrates were 108 V and 10 mL/h respectively. Under certain frequencies shown in Figs. 4.11(c)-(e), there are visible bubbles indicated by arrows...	87
Fig. 4.12	Variation of the mixing efficiency with applied frequency for two different DI water-glycerol solutions. Mixing Fluids are DI water-glycerol solutions with viscosities of 5.69 mPa·s and 44.75 mPa·s under driving voltage 108 V and the flow rate 10 mL/h.	89
Fig. 4.13	The experimentally observed effective working frequency range for achieving good mixing in the DI water-glycerol solutions with various viscosities	90
Fig. 4.14	Mixing patterns of DI water-glycerol solutions with viscosity of 5.69 mPa·s at driving frequencies of 1.5 kHz and 2.5 kHz (a and b). DI water solutions with viscosity of 44.75 mPa·s at driving frequencies of 1.5 kHz and 2.5 kHz (c and d).....	90
Fig. 4.15	The mixing efficiencies for the DI water-glycerol solution with its viscosity of 5.69 mPa·s at different flow rates.	91
Fig. 4.16	A reference device with a straight channel. (a) Structure with straight channel and (b) experimental device. The cross line d-d is chosen to analyze the mixing efficiency.....	92

- Fig. 4.17 Experimental images of the reference device with DI water. (a) The actuation was off. (b) The actuation was switched on at frequency 1.5 kHz. (c) The actuation was switched on at frequency 2 kHz. The applied voltage and the flowrates were 108 V and 10 mL/h respectively.93
- Fig. 4.18 Variation of the mixing efficiency with applied frequency for DI water in the straight channel under driving voltage 108 V and the flow rate 10 mL/h. ..94
- Fig. 4.19 Experimental images of the straight channel reference device for DI water-glycerol solution with a viscosity of 5.69 mPa·s. (a) The actuation was off. (b) The actuation was switched on at frequency 1.5 kHz. (c) The actuation was switched on at frequency 2 kHz. The applied voltage and the flowrates were 108 V and 10 mL/h respectively.95
- Fig. 4.20 Variation of the mixing efficiency with applied frequency for DI water-glycerol solution with viscosity of 5.69 mPa·s under driving voltage 108 V and the flowrate 10 mL/h.95
- Fig. 5.1 The computed transient pressure distributions for the DI water at different actuation frequencies. (a) 0.5 kHz, $t = 0.725T$ (T is the period of the driving voltage), the lowest pressure is 71810 Pa; (b) 1 kHz, $t = 0.643T$, the lowest pressure is 2990 Pa; (c) 1.5 kHz, $t = 0.557T$, the lowest pressure is 380 Pa; (d) 2 kHz, $t = 0.535T$, the lowest pressure 1290 Pa; (e) 5 kHz, $t = 0.5078T$, the lowest pressure is 3000 Pa; and (f) 6 kHz, $t = 0.725T$, the lowest pressure is 7600 Pa. The DI water vapor pressure at 25 °C is 3173 Pa. The flowrate through the mixer is 10 mL/h.100
- Fig. 5.2 The absolute pressure distribution at $t = 0.75T$ (T is the period of the driving voltage) under the actuation frequency 1.5 kHz for DI water-glycerol solutions with various viscosities. (a) $\mu = 0.89$ mPa·s, DI water without

glycerol, the minimal pressure in the channel is 380 Pa, below the water vapor pressure 3173 Pa (Table 4.1); (b) $\mu = 5.69 \text{ mPa}\cdot\text{s}$, the minimal pressure in the channel is 580 Pa, below the water vapor pressure 2568 Pa; (c) $\mu = 44.75 \text{ mPa}\cdot\text{s}$, the minimal pressure in the channel is 1020 Pa, below the water vapor pressure 1649 Pa..... 102

Fig. 5.3 The minimal pressure in the low pressure region at various driving frequencies.

The working fluid is the DI water-glycerol solution with viscosity of 44.75 mPa·s. The water vapor pressure under 25 °C is 1649 Pa. The dashed line represents the water vapor pressure (or $P/P_{\text{water-vapor}} = 1$), below which the bubbles can be generated. 102

Fig. 5.4 The minimal pressure in the low pressure region at various flowrates. The

working fluid is a DI water-glycerol solution with its viscosity of 5.69 mPa·s and the water vapor pressure is 2568 Pa. The dashed line indicates the water vapor pressure (or $P/P_{\text{water-vapor}} = 1$), below which the bubbles can be generated. 103

Fig. 5.5 Experimental setup for observing bubble generation by using a high speed

camera. 104

Fig. 5.6 Different stages of the bubbles generation processes in the mixing channel,

working fluid is degassed DI water and driving frequency is 1.0 kHz. (a) Top view of the mixer, zones 1, 2 and 3 are observation zones. (b) The raw image of zone 1 before switching on the actuation. There are no bubbles. (c) The image of zone 1, 0.02 second after switching on the actuation. Some the initial bubbles occur. Camera setting: 10000 frames per second, 512×512 pixels, 3.5mm×3.5mm. (d) The image of zone 2, 0.6 second after switching on the actuation. The bubbles moving from zone 1 become bigger. Camera

setting: 3000 frames per second, 1024×1024 pixels, 7.0mm×7.0mm. (e) and (f) The images of zone 3, 1.5 second after switching on the actuation. The collision and coalescence of bubbles are observed. Camera setting: 20000 frames per second, 512×256 pixels, 3.5mm×1.75mm.	106
Fig. A.1 Experimental setup for temperature measurement using an infrared camera.	112
Fig. A.2 Temperature measurement at $t = 2$ s after switching on the micropump and micromixer. (a) The micropump at frequency of 70 Hz; (b) the micromixer at frequency of 2 kHz.	113
Fig. A.3 Temperature measurement at $t = 30$ seconds after witching on the actuation of micropump at frequency of 70 Hz.	114
Fig. A.4 Temperature measurement at $t = 15$ seconds after witching on the actuation of micromixer at frequency of 2 kHz.	114

List of Tables

Table 4.1 Dynamic viscosity, density and water vapor pressure of DI water-glycerol mixtures at 25°C	85
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Chapter 1

Introduction

1.1 Background

Microfluidics, which is involved in manipulation of fluids in channels at microscale, has emerged as a distinct new field in mechanical engineering. Microfluidics has the potential to influence many areas, such as chemical synthesis, biological analysis, optics and information technology [1]. There are advantages by using microfluidic systems, including portability, low fluid volumes and little sample consumption, faster analysis and response times, better process control, cost-effective, and less contamination, safer platform for chemical, radioactive or biological studies because of integration of functionality, etc.

The growing importance of microfluidics in life sciences and microengineering technology leads to a fast development of microfluidic devices. Microfluidic devices offer a viable microfluidic platform for miniature and well controlled research. The common microfluidic devices, such as valves, pumps, mixers, actuators, sensors, filters, and separators, are designed to meet the requirement of integration into a lab-on-a-chip (LOC).

Among the large number of microfluidic devices realized up to now, micropumps clearly represent the case of a ‘long runner’ in science. Woias [2] summarized micropumps development in the past two decades from 1978 [3]. Nguyen et al [4] gave a general overview on micropumps in microelectromechanical systems (MEMS). Laser and Santiago [5] discussed micropumps by comparisons regarding maximum measured volumetric flow rate, differential pressure, and overall package size. Recently, Iverson and Garimella [6] provided a review of pumping mechanisms and important new developments in the past few years. Conventional pumps such as

syringe pumps, and regulated sources of pressure or vacuum have been widely used in many microfluidic systems. All these microfluidic systems are passive, and cannot work without external devices and power sources which are often bulky. Therefore, new designs of micropumps that can be fabricated easily and cost-effectively are still attractive. Recently, new transport effects such as electrokinetic effects, acoustic streaming, magnetohydrodynamic effects are getting more attention in microfluidics, owing to their pumping and mixing effects.

Besides micropump, micromixer is another important device in microfluidic systems. The processes, such as deoxyribonucleic acid (DNA) hybridization, cell activation, enzyme reactions, and protein folding, require fast reactions that involve mixing of the reagents and reactants. However, due to small dimensions, the Reynolds numbers (Re) are usually quite low in microchannels, and flow in microfluidic systems is normally laminar. As a result, mixing there is mainly based on molecular diffusion, and long mixing length/time is therefore required and the mixing efficiency is poor [7]. There are several review papers on micromixer [8-11]. These review papers described microstructured mixer devices and their mixing principles concerning liquids and gases. In order to achieve complete mixing within a reasonable time and length scale, new design of effective micromixer that can be fabricated easily is still an attractive research direction.

1.2 Objectives

Motivated by the fundamentals and applications of micropumps and micromixers in microfluidics, this study is an attempt to develop and study new designs for micropumps and micromixers by introducing acoustic features in these devices. The specific objectives are:

- (1) To develop and study micropumps with acoustically featured actuation chambers.
- (2) To develop and study micromixers which enhance the micromixing by oscillating bubbles.

The scope of this research including:

- (1) Design and fabricate valveless micropumps with acoustically featured actuation chamber. Conduct experiments to characterize the pumping effect.
- (2) Carry out numerical simulations on the pumping characteristics and pumping effect. Compare the simulation results with experimental measurements. Investigate the pumping mechanism.
- (3) Design and fabricate micromixers with acoustically featured mixing chamber. Conduct experiments to examine the mixing enhancement in pure DI water, together with the bubble generation characteristics.
- (4) Conduct experiments to examine the mixing enhancement in DI water-glycerol solutions with high viscosities.
- (5) Investigate the bubble generation mechanism in the micromixer.

1.3 Outline of the Thesis

The following are the outlines of the thesis.

Chapter 1 gives general introduction of the research, including the background and objectives.

Chapter 2 presents a literature review on research and technology development in the areas associated with the present study, including various types of micropumps and micromixers, especially valveless micropumps and acoustic micromixers, the particle image velocimetry (PIV) technique and bubble generations in microchannels.

Chapter 3 covers both experiments and numerical simulations on new designs of valveless micropumps. Detailed device configurations, fabrication, experiments setup and measurements are described. A numerical simulation is carried out based on a simplified two-dimensional flow model. The detailed numerical model, equations and parameters are presented. A synchronized PIV technique is developed to carry out experimental study of the transient flow fields in the micropump. The PIV technique and the results are also given in details.

Chapter 4 provides studies of a design of micromixer. The details of the design, fabrication and characterization of the mixing enhancement are presented. The mixing is achieved by oscillating bubbles which are generated in the mixing fluids.

Chapter 5 focuses on the bubble generation mechanism in the micromixer by both experimental observation and numerical simulations.

Chapter 6 concludes the main results and findings from the present study. Recommendations are also highlighted in this chapter as the further work.

Chapter 2

Literature Review

2.1 Introduction

In microfluidics, fluids pumping and mixing are important microfluidic functions. Numerous micropumps and micromixers based on different kinds of technology have been developed, in order to meet the requirement arisen from the micro/nano technologies.

The first scientific paper on a micropump published in 1978 [3], and the interest in micropump has grown fast since then, leading to widespread research activities in this area. Several review papers on micropump have been published [2, 4-6, 11-13]. Based on the multitude of fluidic designs, actuation principles and fabrication technologies, micropumps can be divided into multidimensional classifications. We classify micropumps into two main categories: mechanical micropumps and nonmechanical micropumps.

Similar to micropumps, there are several review papers on micromixer [8-11]. These review papers described microstructured mixer devices and their mixing principles concerning liquids and gases. Micromixers are usually categorized as passive micromixers and active micromixers. Passive mixers utilize geometrical advantages to enhance mixing and they do not require external driving. Mixing concepts include lamination arrangements, splitting and recombining streams, chaotic advection, droplet, and injection in flow. Active mixers utilize external driving forces to disturb the flow to enhance mixing. Examples are the mixing devices using oscillating pressures, magneto-hydrodynamic effect, electro-hydrodynamic effect, electrokinetic effect, and acoustic effect, etc.

This chapter presents a literature review on various types of micropumps and mixromixers, including mechanical micropumps, nonmechanical micropumps, passive micromixers, and active micromixers. PIV measurement method is also included. At last part, the current study of bubble generation in microchannel is briefly reviewed.

2.2 Mechanical Micropumps

Mechanical micropumps are defined as those that utilize moving solid-fluid structures, such as check valves and oscillating membranes, to transfer a constant fluid volume in each pump cycle. The mechanical pumps need a mechanical actuator, which converts electric energy into mechanical work. Shoji and Esashi [14] discussed two main actuator categories: external actuators and micromachinable actuators. The external actuators include disk type, cantilever type, piezoelectric actuation, pneumatic actuation, and shape memory alloy and bias spring. These are shown in Fig. 2.1. The micromachinable actuators include electrostatic actuators, thermopneumatic actuators, electromagnetic actuators, and bimetallic actuators, which are illustrated in Fig. 2.2.

Fig. 2.1 Schematic of the external actuators used in microflow control devices. (a) Electromagnetic; (b) Piezoelectric bimorph (Disk Type); (c) Piezoelectric bimorph (Cantilever Type); (d) Piezoelectric stack; (e) Pneumatic; (f) Shape memory ally and bias spring. [14]

Fig. 2.2 Schematic of the micromachinable actuators used in microflow control devices. (a) Electrostatic actuator; (b) Thermopneumatic actuator; (c) Electromagnetic actuator; (d) Bimetallic actuator. [14]

2.2.1 Check-valve Pumps

A typical check-valve pump is comprised of a pumping chamber with a flexible membrane on one side (or two), and the chamber is connected to two check-valves, which is opened by the critical pressure difference Δp_{crit} for flow rectification. The general structure of a check-valve pump is depicted in Fig. 2.3. The upward movement of the membrane increases the pump chamber volume, which is called a supply mode. When chamber Δp becomes lower than the inlet valve's threshold pressure Δp_{crit} , the inlet valve is open and the fluid is sucked in. The downward movement of the membrane decreases the pump chamber volume and increases the chamber pressure. When the chamber Δp becomes higher than the outlet valve's threshold pressure Δp_{crit} , the outlet valve opens and fluid in the pump chamber is transferred from the pump chamber into the outlet.

Fig. 2.3 Principle construction of a mechanical micropump and check valves [2].

The first micropump with passive check-valves was presented by Van Lintel in 1988 at the University of Twente [15]. As shown in Fig. 2.4, a two-valve and a three-valve pump having two glass layer sandwiched an entire etched 2 inch silicon wafer structure were actuated by a piezoelectric disk. The pumps membrane and valves were 12.5 mm and 7 mm diameter, respectively. For the two-valve pump, with 100 V drive voltage, a stroke volume of 0.21 μL , and a maximum flow rate of 8 $\mu\text{L}/\text{min}$ at 1 Hz were obtained. For the three-valve pump, with an actuation voltage of 125 V, a stroke volume of 0.30 μL , and a maximum flow rate of 0.6 $\mu\text{L}/\text{min}$ at 0.1 Hz frequency were observed.

Fig. 2.4 Micro diaphragm pumps with piezoelectric actuation and passive membrane valves. (a) Two-valve pump; (b) Three-valve pump. [15]

The same valve structures were also used by Van den Pol et al. [16], driven by thermopneumatic actuators instead of piezoelectric actuators. Thermopneumatic actuation occurs when the volume expansion or induced stress of a material, usually a thin film resistive heater, in response to applied heat. In Van den Pol's valve, a secondary fluid separated from the pump fluid was heated to expand and deflect the pump diaphragm. The pump membrane was actuated by the dynamic pressure of an amount of gas contained in a cavity, controlled by resistive heating. At a supply voltage of 6 V, the maximum flow rate of 34 $\mu\text{L}/\text{min}$ was demonstrated with a maximum backpressure of 0.05 atm.

2.2.2 Peristaltic Pumps

The principle of a peristaltic piezoelectric fluid pump was developed in 1980s at Stanford University by Smits [17]. The pump comprising three active valves in line is illustrated in Fig. 2.5. Etched silicon wafer was sealed on both sides with glass plate. Piezoelectric disks were bonded to the glass above each of the three pump chambers etched in silicon wafer. Peristaltic pumping was achieved by sequential activation of the piezoelectric actuators as shown in Fig. 2.5. A maximum flow rate of 100 $\mu\text{L}/\text{min}$ and a maximum backpressure of 0.6 mH₂O were reported.

Fig. 2.5 Peristaltic micropump: schematic representation of the valve actuation scheme for pumping from inlet to outlet (top to bottom). [17]

2.2.3 Valveless Rectification Pumps

The valveless rectification pumps use diffuser/nozzle or valvular conduit structures to replace check-valves for flow rectification. The working principle of a diffuser/nozzle is shown in Fig. 2.6. In the supply mode, the chamber volume is increased by actuation, the inlet element acts as a diffuser and the outlet element acts as a nozzle for the liquid flowing into the chamber, resulted in more fluid being transferred through the inlet than through the outlet. In the pump mode, conversely, the chamber volume is decreased by actuation, the inlet element acts as a nozzle and the outlet element acts as a diffuser for the liquid flowing out of the chamber, resulted in more fluid being expelled through the outlet than through the inlet. The result for a complete pump cycle is a net flow generated from the inlet to the outlet.

Fig. 2.6 Schematic pumping principle diffuser/nozzle valveless micropump. (a) Supply mode; (b) Pump mode. [18]

The first diffuser/ nozzle valveless micropump was presented by Stemme [18]. The pump was fabricated in brass as shown in Fig. 2.7. With an active diaphragm diameter of 19 mm, the maximum flow rate of 16 mL/min and maximum pump pressure about 2 mH₂O were demonstrated.

Fig. 2.7 Valveless rectification micropump with piezoelectric actuation. [18]

Olsson et al. [19] presented a valveless planar fluid pump with two pump chambers. Fig. 2.8 shows the top and bottom view of the planar pump. The antiparallel configuration reduced inlet and outlet pressure pulses and increased the pump flow performance. When the diaphragms were excited at the pump resonance frequency of 540 Hz, the maximum flow rate of 16 mL/min and the maximum pump pressure of 1.7 mH₂O were reported. The same group [20] investigated the diffuser element micromachine and design in valveless micropumps. Fig. 2.9 shows scanning electron microscope (SEM) photos of a diffuser element etched isotropically and etched depth of 80 μm . In order to understand the flow behavior of diffuser/ nozzle elements, Olsson [21, 22] conducted a numerical simulation of diffuser/nozzle elements in valveless micropumps. Using ANSYS/FLOTTRAN software, the flow dynamics in the diffuser and the nozzle elements were simulated. The difference in the flow patterns for diffuser elements and nozzle elements explained the opposite positive flow directions. The diffuser element took advantage of the pressure recovery in the diffuser and had the positive direction in the diverging-wall direction. The nozzle element had gross flow separation in the diverging-wall direction and the ‘vena-contracta’ effect instead of pressure recovery. Olsson et al. [22] had a further numerical simulation on the valveless diffuser pump using a lumped-mass model.

Fig. 2.8 Valveless planar micropump: top and bottom view. [19]

Fig. 2.9 SEM photos of a diffuser element. (a) Etched isotropically; and (b) Etched depth of 80 μm . [20]

Numerical simulation makes it possible to predict the flow-pressure characteristics at different working conditions for valveless micropumps. Nguyen and Huang [23] reported a numerical simulation of pulse-width-modulated diffuser/nozzle micropumps. The vibration of the membrane was modeled by either a moving wall or moving velocities as boundary condition. The interaction between the structure and fluid was neglected in the simulations. Nguyen and Huang [24] manufactured the valveless miniature pump by using printed circuit board (PCB). The maximum flow rate delivered by this pump can reach to 3 mL/min, and the experimental results were compared with the numerical results. The deforming curve of the membrane in the simulation was assumed following Timoshenko's theory [25]. Fig. 2.10 shows the simulated velocity field inside the diffuser/nozzle pump.

Fig. 2.10 Simulated velocity field inside the diffuser/nozzle pump in (a) Supply mode; (b) Pump mode. [24]

Singhal et al. [26] investigated flow characteristics of low Reynolds number laminar flow through diffuser/nozzle elements in valveless micropumps. Software FLUENT was used to model four different types of diffuser flows. Wang et al. [27] presented a finite element analysis (FEA) method which was suitable for guiding the design and predicting the performance of a micropump actuated by a piezoelectric actuator. The structure of the pump was optimized including the thickness of pump membrane, the diameter of pump chamber, and the size of piezoelectric ceramic. Li et al. [28] used commercial finite element analysis software COMSOL Multiphysics to simulate electro-fluid-structural interaction of a piezoelectric micropump. Jeong and Kim [29] compared two different numerical models for evaluation of the performance characteristics of a valveless piezoelectric micropump. In their studies, the dynamic characteristics of the piezoelectric disk and the flow characteristics at the inlet and outlet were evaluated for different frequencies.

Lu and Wu [30] presented a two-dimensional fluid mechanics model to approximate periodical flows of a micropump, in which the valveless piezoelectric micropump was simplified to a two-dimensional thickness-averaged flow coupled with diaphragm vibration. The natural frequencies, diaphragm vibration shapes and relationship of diaphragm amplitude and frequency were predicted by the simulation. Yang et al. [31] utilized commercial software CFD ACE+ 2002 for the simulation and analysis of the flow characteristics inside a valveless micropump. Flow module and grid deformation module were used. They numerically investigated the performance of a valveless micropump affected by the driving frequency, opening angle, geometric dimension, and amplitude, etc. Cui et al. [32] built a complete electric-fluid-solid coupling model using ANSYS software to investigate the behaviors of the valveless micropumps. Simulation and optimization of the micropump for medical applications were studied. By taking the optimal thickness of the piezoelectric layer which was affected by the material and the thickness of the pump membrane, a large pump flow was obtained.

Being different from using commercial software, Tsui and Lu [33] presented a computational procedure to study the flow of a valveless micropump using the fully conservative finite volume method and a lumped-system analysis in unstructured mesh.

Rather than using numerical simulation to study the flow field, Nabavi et al. [34] investigated the flow structure inside a standing wave valveless pump by experimental observations. The pumping flow and acoustic streaming velocities flow fields in the chamber at different phases of the excitation signal were measured using the synchronized PIV technique. Also, the interaction of three flow fields was studied. They showed that the pumping flow had a slight effect on the acoustic velocity patterns, while the streaming velocity structures were drastically affected by the pumping flow. More PIV measurements in micropump are reviewed in section 2.6 of this chapter.

The second type of valveless micropump with dynamic passive valves was presented by Gerlach et al. [35, 36]. As shown in Fig. 2.11, the pump with a large opening angle of 70.5 degree worked in the opposite direction compared with the earlier presented valveless diffuser pump.

Fig. 2.11 The valveless micropump with dynamic passive valves. [35, 36]

Fig. 2.12 (a) Valvular conduit pump; (b) The tesla valve. [37]

The third type of valveless micropump was proposed by Forster et al. [37]. As shown in Fig. 2.12, a valvular conduit worked as flow direction element. Tesla valves were used to replace the diffuser/nozzle element.

2.3 Nonmechanical Micropumps

2.3.1 Electrohydrodynamic Pumps

Electrohydrodynamic (EHD) pumps are operated based on the interaction of electrostatic forces with ions in dielectric fluids. The force density F_d is given by Bart [38] as

$$F_d = q_f E + P \cdot \nabla E - \frac{1}{2} E^2 \nabla \epsilon + \nabla \left(\frac{1}{2} \rho \frac{\partial \epsilon}{\partial \rho} E^2 \right) \quad (2.1)$$

where q_f is free space-charge density, E is electric field, P is the polarization vector, ε is the fluid permittivity, and ρ is the mass density.

In a review paper by Nguyen et al. [4], the EHD induction pump is based on the induced charges at the material interface, and the induced charges along the wave direction are dragged and pulled by a traveling wave of electric field. The first micromachined EHD induction pump was developed by Bart et al. [38]. Similar designs were followed by Fuhr et al. [39, 40] and Ahn et al. [41]. In the EHD injection pump, the Coulomb force acts on the injected charges, moving ions injected from one or both electrodes by means of electrochemical reaction. Richter and Sandmaier [42] reported a micromachined electrohydrodynamic micropump based on such charge injection. By using ethanol as the working fluid, a maximum static pressure of 2.5 kPa and a flow rate of 14 mL/min were achieved. They demonstrated the maximum flow rate and pressure head could be varied in a wide range by adjusting the dimensions of the pump.

2.3.2 Electrokinetic Pumps

Electrokinetic pump is one of the successful micropumps for commercial applications. There are electrophoresis and electroosmosis in electrokinetic phenomenon. Electrokinetic pumps utilize the electrical field for pumping conductive fluid.

Zeng et al. [43] fabricated an electroosmotic micropump by packing the 3.5 μm diameter non-porous silica particles into 500-700 μm diameter fused-silica capillaries. Under 2 kV applied voltage, pressure head of 20 atm pressure and flow rates of 3.6 $\mu\text{L}/\text{min}$ were achieved, which were much higher than that without the silica particles. Chen et al. [44] developed a multi-stage electroosmotic pump. Wang et al. [45] gave a comprehensive review on electroosmotic pumps.

2.3.3 Magnetohydrodynamic Pumps

Magnetohydrodynamic (MHD) pumps utilize the Lorentz effect, which is generated when a current-carrying conductor is placed in a magnetic field. The Lorentz force F_L is given by

$$F_L = I \times Bw \quad (2.2)$$

where I is the electric current across the pump channel, B the magnetic field strength and w the distance between the electrodes.

Jang and Lee [46] presented a MHD micropump. The pressure head was 18 mm at electric current 38 mA and the flow rate was 63 $\mu\text{m}/\text{min}$ at an electric current 1.8 mA, respectively. Lemoff and Lee [47] demonstrated an AC MHD micropump compatible with pumping fluid containing biological specimens. In a 1 M NaCl solution, a maximum flow velocity of 1.51 mm/s was achieved.

2.4 Passive Micromixers

Passive micromixers do not require external agitation and the mixing concept relies mainly on diffusion as well as chaotic advection. The mixing can be improved by increasing the contact surface between two different mixing fluids causing the diffusion. Passive micromixers have advantages of easier fabrication and integration than active micromixers. Passive micromixers include lamination mixers, chaotic mixers, and droplet mixers, etc.

2.4.1 Lamination Mixers

Among passive micromixers, lamination mixer is the well-known type of mixers. Bi-lamination has two basic flow structures: T- and Y- flow structures [48, 49]. Multi-lamination micromixers are based on several concepts, such as bifurcation feeds [50], interdigital parallel flow [51-55], hydrodynamic focusing [56-59], splitting recombination and rearrangement [51, 56, 60]. Lamination mixers split the inlet streams into n ($n \geq 2$) substreams, then recombine them into one stream, so as to increase the contact surface between mixing fluids.

Branebjerg et al. [51] presented a micromixer based on multi-layer lamination including a separation plate inside the microchannel. Gobby et al. [49] studied the mixing characteristics in micromixer with various T-type design for gaseous flow; and simulated the mixing performance altering the mixing length, the angle between the inlet channels. Recently, Abonnenc et al. [61] numerically studied lamination mixer-reactor focusing on influence of the diffusion coefficient and flow rate ratios.

2.4.2 Chaotic Mixers

Advection is an important transport form of mass in flows. Chaotic advection can improve mixing in microchannels significantly. When chaotic mixer is achieved by special geometries, it belongs to passive mixers category, when chaotic mixer is driven by an external force, it is called active mixer. Only passive chaotic mixers are reviewed in this section.

The first micromixer utilized chaotic advection was presented by Stroock et al. [62]. Transverse flows were created in microchannels to induce chaotic stirring at low the Re number. Two different patterns of grooves on the floor of the channel were investigated. One was slanted groove; the other was staggered herringbone groove. The staggered herringbone structure reduced the required mixing length, which grew logarithmically with the Peclet number (Pe). The staggered herringbone mixer (as shown in Fig. 2.13) performed well at Re number less than 100. By surface modification in a micromixer, application in electrokinetic flows can be found [63]. Wang et al. [64] investigated the mixing effect of chaotic advection with the slanted groove in Stroock's paper. Computational fluid dynamics (CFD) simulations and particle tracking technique were used to study mixing in microchannels with patterned grooves. Chaotic flow can be created for high aspect ratio grooves. The simulation results proved that the transverse motion could fold and stretch fluids to increase their interfacial area and enhance mixing.

Fig. 2.13 Staggered herringbone mixer (SHM). (a) Schematic diagram of one-and-a-half cycles of the SHM; (b) Confocal micrographs of vertical cross sections of a channel as in (a). [62]

Fig. 2.14 Micromixer designs for mixing with chaotic advection [10]. (a) Slanted ribs; (b) Slanted grooves [62, 63]; (c) Staggered-herringbone grooves [62, 63]; (d)(e)(f) Patterns for surface modification in a micromixer with electrokinetic flows [65]; (g) Modified Tesla structure; (h) C-shape [66]; (ii) L-shape [67]; (j) Connected out-of-plane L-shape [68]; (k) Twisted microchannel [69]; (l)(m)(n) Other designs of twisted channel [70]; (o) Obstacles on wall [71]; (p) Obstacles in the channel [64]; (q) A zig-zag-shaped channel [72].

Fig. 2.14 shows various micromixer designs for mixing with chaotic advection. More studies on chaotic micromixers were conducted at low Re numbers as shown in Fig. 2.14 (a)-(f) [62, 63, 71, 73-76], intermediate Re numbers as shown in Fig. 2.14 (g)-(n) [66-70], high Re numbers as shown in Fig. 2.14 (o)-(q) [71, 72, 77, 78].

2.4.3 Droplet Mixers

Mixing can be achieved by forming droplets in the mixed liquids, which reduces the mixing path and increases the mixing efficiency. The moving of the droplet produces an internal flow field and makes mixing inside the droplet possible. The first droplet micromixer was reported by Hosokawa et al. [79]. A hydrophobic microcapillary vent was used to join the two initial droplets. The droplets are generated and transported using pressure effects. Beside pressure effects, capillary effects such as thermocapillary [80] and electrocapillary effects such as electrowetting [73, 81] can be used to transport droplets.

Paik et al. [81] presented a droplet micromixer with the electrowetting concept. The effects of varying droplet aspect ratios were studied on linear-array droplet mixers. The results showed that an optimal aspect ratio for four electrode linear-array mixing was 0.4 with a mixing time of 4.6 s. The rapid mixing was achieved by using repeated mixing and splitting operations in droplets. Chang and Yang also reported a droplet micromixer based on electrowetting concept for the integrated Polymerase chain reaction (PCR) chip [73]. After three cycles of the counterclockwise motion in the specific loops, the mixing efficiency of the merged droplet was increased to 92.8% from 20.5% when two droplets were initially merged.

The other droplet micromixers took advantage of flow instability between two immiscible liquids. The carrier liquid can be perfluorodecalin [82], fluorinated oil FC-40 containing fluoro alcohol surfactant [83, 84], and light mineral oil or sunflower oil [85].

2.5 Active Micromixers

2.5.1 Pressure Driven Mixers

One of the earliest ways to achieve active mixing in microstructured devices is by pressure field disturbance. Deshmukh et al. [86] reported a micromixer with pressure disturbance. The micromixer was integrated with a planar micropump which drove and stopped the flow in the mixing channel. Ma et al. [87] investigated an unsteady T-form micromixer driven by pressure disturbances. High-order numerical schemes were used to study the performance of T-mixer and the best mixing condition. Numerical results were compared with experimental results. The results showed that the best mixing condition in terms of the Strouhal number (St) was found to be 0.42 for the flow Re numbers less than 0.24.

The pressure disturbance can be generated in micromixers by pulsing velocity [88], by an integrated magnetic microstirrer [89], and by introducing a computer controlled source-link system [90]. In Niu and Lee's work [90], the mixing effect was related to the pulse frequency and the number of mixing units. Okkels and Tabeling [91] modeled the mixing pattern in the chamber in a pressure driven micromixer.

2.5.2 Electrokinetic Mixers

Compared to pressure driven flow, electro kinetic flow can be used to transport liquid in microchannels. Electrokinetic phenomena have been widely used in microfluidic mixing. Because of simplicity and ease of integration to microfluidic chips, electrokinetic mixers are favorable among active micromixers. Oddy et al. [92] reported a micromixer taking advantage of fluctuating electric fields to effect mixing. Sinusoidal oscillation electric fields strengths in excess of 100 V/mm were applied for channels with dimensions of about 50 μm . In the mixing chamber, rapid stretching and folding of the fluorescence tracer were observed. A mixing time of 2.5 s for a mixing volume of 0.1 μL was achieved. Other studies also utilized an electrokinetic instability to enhance mixing in a microchannel [93, 94]. Similarly, Leu and Ma [95] used the transverse electro-hydrodynamic forces to promote a mixing environment. Erickson

and Li [96] investigated the influence of surface heterogeneity on electrokinetically driven microfluidic mixing.

Johnson and Locascio [97] utilized electroosmotic flow to create mixing via non-axial flow generation in channels with oblique grooves. Glasgow et al. [98] reported a micromixer relied upon electroosmotic flow. Other studies [99-101] created heterogeneous channel surface charges in electroosmotic micromixers. Wu and Liu [101] report an electrokinetic micromixer and achieved the good mixing efficiency over 90% after the solutions pass through a 5 mm long microchannel. Pacheco [102] investigated two methods to enhance mixing in an electroosmotic flow of an electrolyte solution flowing inside a three-dimensional microchannel. The mixing enhancement was achieved by modulating the initially time-periodic electric field. The mixing was optimal and Taylor dispersion effects were minimized with the randomization protocol based on the selection of intervals of varying length.

2.5.3 Acoustically Actuated Mixers

Acoustic waves can be used to stir fluids and induce mixing in micromixers. Moroney et al. [103] reported the concept of acoustic mixing in microscale firstly. Zhu and Kim [104] presented an acoustic wave liquid mixer. The loosely-focused acoustic waves were generated by piezoelectric zinc oxide thin film. Frequency of 240 and 480 MHz sinusoidal wave were applied. Miniature valveless ultrasonic pumps and mixers were developed by Rife et al. [105], in which the mixing effect can be improved by using acoustic streaming. Vivek et al. [106] reported the simulation and experimental results of three electrode patterns acoustic wave micromixers.

Fig. 2.15 Schematic drawing of the cross section of the mixing chamber in an ultrasonic micromixer. [107, 108]

Yang et al. [107, 108] designed an ultrasonic micromixer based on ultrasonic vibration produced by a PZT (PbZrTiO_3 lead-zirconate-titanate) diaphragm. The micromixer worked effectively at 48 kHz and 150 Vpp, or 60 kHz and 50 Vpp. The mixer chamber was fabricated using silicon wafer covered with glass as shown Fig. 2.15. Water and ethanol were used as mixing fluids. However, it still required long time to achieve complete mixing in this device. Another drawback was that the rate of mixing could not be increased with input power and there was a problem associated with temperature rise induced by high-frequency ultrasonic irradiation.

Fig. 2.16 Schematic drawing of air pockets on the inner wall of the mixing chamber of bubble-induced acoustic micromixer. [109, 110]

As shown Fig. 2.16, Liu et al. [109, 110] developed an acoustic micromixer relying on bubble oscillation to induce secondary flow which was similar to a sink-source flow pattern. The behavior of bubbles in acoustic field depended on resonance characteristics. Numerical simulations showed that the induced flow field and mixing efficiency were determined by bubbles positions. It was demonstrated that complete

mixing can be achieved within several tens of seconds, with a significant improvement compared with the mixing time reported by Yang et al. [108]. Low energy was consumed with 2.0 kHz and 5 Vpp. However, foreign gas bubbles were needed to be introduced and trapped on the mixer chamber wall. Air pockets with 500 μm diameter and 500 μm depth were used to trap the air bubbles. Further, the micromixing technique using acoustic streaming principle was developed to accelerate DNA hybridization process or to increase the immunomagnetic cell capture process efficiency [108, 109, 111].

Yaralioglu et al. [112] utilized acoustic streaming to stir flow in Y-type mixer. The zinc oxide thin film as transducer was excited at 450 MHz. The performance of the mixer was characterized by mixing phenolphthalein solution and sodium hydroxide dissolved in ethyl alcohol. Yu et al. [113] utilized acoustic streaming effect to transport and mix fluids. Fu et al. [114] described ZnO thin film based surface acoustic wave micromixer and micropump.

2.5.4 Magnetohydrodynamic Mixers

Magnetic effect can also be used to achieve mixing. Active micromixer utilizing magnetic forces is another important class of mixing [8, 10]. In the presence of a magnetic field, the coupling between the magnetic and electric fields generates Lorentz forces which induces transversal movement of fluids in the mixing chambers. A miniature magnetohydrodynamic micromixer was presented by Bau et al. [115]. By applying alternating potential differences across pairs of electrodes, currents were induced in various directions to enhance mixing. The electrode arrays printed with a gold paste were deposited on the conduit's surface in the transverse direction. West et al. [116] utilized arrays of electrodes deposited on the walls of silicon or SU-8 based microchannel. The MHD mixer agitated fluids and induced secondary complex chaotic flows. Lu et al. [89] reported the design and fabrication of a microstirrer and its array for micromixing. The mixing efficiency could be enhanced by increasing the stirring speed. Ryu et al. [117] reported a MHD micromixer driven by an external rotating magnetic field. The channel was made of Polydimethylsiloxane (PDMS). The mixing effect in a channel was improved by increasing the ratio of blade thickness to channel

height. The drawback of MHD micromixer was that active mixing could only work for conductive fluids.

2.6 PIV Measurement

Understanding of the behavior of fluid flow is essential to successful designs and optimal control of microfluidic devices. Numerical simulations are well known to be useful to predict flow characteristics under various conditions. Flow visualizations are also useful methods in getting direct flow patterns and characteristics.

Particle image velocitmetry (PIV) is a widely used technique for measuring flow fields [118, 119]. In the PIV technique, a laser light sheet is pulsed twice with a known time separation between the two pulses. A camera captures the images of the tracer particles in fluids. The velocity field is resulted from the displacement of particles divided by the time separation. There are review papers on PIV technique development. Grant [120] discussed the evolution of PIV from its various roots, the importance of these roots and their influence on fluid mechanics. Adrian [121] reviewed the development and current status of PIV over last twenty years. Melling [122] discussed suitable tracer particles for PIV technique, including the particle size, flow tracking capability, tracer particle materials.

Due to the fast development of flow visualization techniques, micro-PIV technique has recently been used to measure the flow fields in microfluidic channels. Santiago et al. [123] firstly conducted micro-PIV experiment to record the flow around a 30 μm diameter cylinder in a Hele-Shaw flow cell. And later they [124] developed micro-PIV system to measure velocity fields with order 1 μm spatial resolution. The accuracy of the PIV system was demonstrated by measuring a known flow field in a $30\mu\text{m} \times 30\mu\text{m}$ microchannel. Nabavi et al. [125] investigated acoustic and streaming velocity fields simultaneously in a standing-wave rectangular channel using synchronized PIV technique. Their PIV system had an electronic circuit to generate a trigger signal in order to synchronize the acoustic waves and PIV lightings. They also analyzed the flow structure inside a valveless standing wave pump using similar synchronized PIV technique[34] Tanake et al. [126] built an improved control circuit to evaluate

performance of a valveless piezoelectric micropump. Sheen et al. [127] studied the flow characteristics using an externally triggered micro PIV technique. An Nd-YAG laser double pulsing at 15 Hz was used to illuminate the flow field. The seeding particles were the fluorescent particles with mean diameter 1 μm . The velocity and vortices fields in the micromixer were studied experimentally. The results showed that the flow recirculation occurred upstream the obstacles and along the lateral direction of the triangular structures. Later, the same micro PIV system was used to measure the full field flow in an obstacle-type PZT valveless micropump [128]. They examined experimentally the characteristics of the high frequency periodic unsteady flow in the micropump. The quantitative measurements provided critical insights into the flow behaviors. Hsu and Sheen [129] also measured the transient motions of the valve and the flow behaviors in a micropump using micro PIV technique. The results revealed that the valve efficiency depended on the mass inertia of the moving part, excitation frequency, and voltage.

2.7 Bubble Generation in the Microchannel

In the early stage of the microfluidics development, bubbles were largely regarded as necessarily avoided in microfluidic devices because they often caused clogging problems in narrow microfluidic passages. However, as many control mechanisms over bubbles have been developed, interests have transitioned from avoiding microbubbles in microchannels to harness them for actuating and regulating the surrounding fluids.

Garstecki et al. [130] demonstrated the process of formation of droplets and bubbles in microfluidic T-junction geometries. They found that dominant contribution to the dynamics of break-up was due to the pressure drop across the emerging droplet or bubbles. They also developed mixing enhancement with bubbles for portable microfluidic devices [130].

Marmottant and Hilgenfeldt [131] conducted experiments using microbubbles fixed on a substrate and driven by ultrasound. 10-100 μm radius bubbles were generated by syringe injection of air. A piezoelectric transducer provided a standing-wave

ultrasound field inside a corvette, which was filled with a suspension of either cells or lipid vesicles. Marmottant and Hilgenfeldt [132, 133] also investigated the potential of using ultrasound-driven gas bubbles as actuators for steady microfluidic flow. The microbubbles were driven to oscillations by the ultrasound. The position and volume of the microbubbles did not change significantly. A steady streaming flow in the microscale was produced as the induced flow. Marmottant et al. [134] studied how to harness the power of bubble streaming, in an experiment, to obtain transport flow with high velocity. Microfluidic transport was achieved without pressure gradients and without microchannels, eliminating precautions against bubbles clogging of channels in two-phase applications.

Pre-design structure has been used as a method to trap bubbles in microchannels. Liu et al. [109, 110] developed an acoustic micromixer using acoustically induced bubble oscillations. Air bubbles were generated and trapped in a chamber with micromachined air pockets and setting into vibration using the sound field generated steady circulatory flows. Ahmed et al. [135] also took the advantage of pre-designed structure in microchannels to trap bubbles. Their structure was a “horse-shoe” shape located between two laminar flows inside a micromixer. An air bubble was trapped in the “horse-shoe” and disrupted the laminar flows by excitation of acoustic wave at its resonance frequency. The same group [136] also developed grooves on the sidewalls of a microchannel to trap more bubbles in the channel.

Micropipette with ultrasound is another method on bubble generation. Ichikawa et al. [137] injected nitrogen gas using a glass micropipette into ethanol flowing in a rectangular ($100\mu\text{m} \times 200\mu\text{m}$) microchannel on PDMS. Gas and liquid flow rates were regulated using mass flow controllers. PZT provided the external actuation over a range of operating voltages (2 to 200 Vpp) and frequencies (50 to 60 kHz). Flow visualization was conducted using a high-speed camera to observe the process of the bubble generation. High speed photography [138-141] has been popularly used to study bubbles in microchannels for a better understanding of the bubble dynamics.

Chapter 3

Valveless Micropumps with Acoustically Featured Microfluidic Chambers

3.1 Introduction

In this chapter, two new designs of valveless micropump with an acoustically featured chamber are studied. One of the designs is the valveless micropump with buffers at inlet and outlet, the other is of straight inlet and outlet without the buffers. Experiments are described in details, including device design, fabrication, experimental setup, and measurements. Experimental characterizations of the pump performance are focused on flow rates and pressures generated by the two pumps. Numerical simulations are conducted for both micropumps. The simulations are based on a two-dimensional model to investigate the flow behaviors inside the pumps. Comparisons of the pump flow rate obtained from experiment and simulation are presented and discussed. The detailed flow patterns associated with the pumping circles are observed by a simple synchronized PIV method. The PIV technique is used to measure the flow velocity fields in the pump chamber, and the results are compared with the flow streamlines generated by the numerical simulations.

3.2 Experiments

3.2.1 Device Design and Fabrication

Fig. 3.1 Schematics of the planar valveless pump.

The valveless micropumps were designed and fabricated using the lamination technology. Both pumps consisted of a circular actuation chamber, a nozzle-shape channel at one end, and a straight channel at other end. One pump had buffer areas at its inlet and outlet. Fig. 3.1 shows the schematics of the pump with buffers. The pump consisted of two Polymethylmethacrylate (PMMA) layers sandwiched with a dry double-sided adhesive layer (Adhesives Research, Inc., Arclad 8102 transfer adhesive). Fig. 3.2 depicts the assembly concept of the planar micropumps.

Fig. 3.2 Stacked concepts of the micropumps. (a) Pump without buffer; and (b) Pump with buffers.

The top PMMA plate with 2 mm thick had two access holes for inlet and outlet, and a 22mm diameter opening to accommodate a piezoelectric disk (Model number BZ21C15NS, purchased from AL Goodwell Industries Ltd). The piezoelectric disk was formed by a 15 mm diameter layer of piezoelectric ceramic glued on the top of a 0.1 mm thick, 22 mm diameter brass sheet. Fig. 3.3 shows the photograph of the piezoelectric disk used in the experiments. The brass sheet was directly in contact with the liquid in the pump. The piezoelectric disk worked as both actuator and pump membrane.

Fig. 3.3 Photograph of a piezoelectric disk.

The circular chamber and channels had a uniform height 300 μm , which was controlled by the double-sided adhesive tape layers number in fabrication. The pump chamber design was drawn using CorelDraw (Corel Co., Canada). Fig. 3.4 shows the details of the pump chamber. The chamber consisted of two parts, a 16 mm diameter circle chamber to accommodate the piezoelectric disk and a nozzle-shape channel with an acoustically featured profile. The overall profile of the chamber is given by

$$y = \begin{cases} \sqrt{8^2 - x^2} & , \quad -8 < x \leq 4; \\ 0.5e^{0.1011(30-x)} & , \quad 4 < x \leq 30. \end{cases} \quad (3.1)$$

The coordinates x and y are defined in Fig. 3.4. A similar design of the chamber was used for an acoustic resonator by Luo et al. [142], in order to obtain a strong resonance pressure.

Fig. 3.4 Geometry of the pump with acoustically featured chamber. (a) Pump without buffer and (b) pump with buffers.

The acoustically featured chamber was extended to the openings through two 10 mm long and 1 mm wide straight channels, as shown in Fig. 3.4. As indicated by the arrow

in Fig. 3.4a, the pumping direction for the pump without buffer is along the nozzle directions, from left to the right, while the pumping direction for the pump with the buffers at inlet/outlet is reversed, as indicated by the arrow in Fig. 3.4b. Two glass capillaries with inner diameter of 3.5 mm were connected to the inlet and outlet of the pump. The glass capillaries and the piezoelectric disk were fixed to the top PMMA plate by epoxy to make sure that there was no leakage. The bottom PMMA plate had thickness of 1 mm and was used to cover the pump chamber. All three layers were bonded and hermetically sealed. Each layer was cut and engraved with a CO₂ laser system (Universal M-300 Laser Platform, Universal Laser Systems Inc., Arizona, USA). Fig. 3.5 shows an assembled micropump.

Fig. 3.5 Assembled micropump with buffers. The bottom photo of the micropump is filled with fluorescent dye solution, which is only for clear description of the pump chamber with buffers.

3.2.2 Experimental Setup and Measurement

De-ionized (DI) water was used as the working fluid throughout the experiment. The pumps were characterized by measuring pumping flowrate and pressure head. The piezoelectric disk as the actuator was driven by a signal generator (33120A, Hewlett Packard, USA) and an amplifier (790, PCB Piezotronics, USA), in which the sinusoidal signal from the signal generator was amplified 30 times.

3.2.2.1 Pump pressure measurement

To measure the maximum back pressure at zero flowrate, the glass capillaries were positioned vertically, as show in Figs. 3.6 and 3.7. The pumping pressure head was characterized by measuring the meniscus positions of water-air interface in the capillary tubes.

The pumping pressures are measured with the following preparative procedures:

- (1) Inject the DI water into pump tube by using syringe. Avoid air bubbles in the pump chamber by repeating injection. Check the existence of bubble before fix the pump vertically on table.
- (2) Accomplish the connections of signal generator, voltage amplifier, and actuator unit. Check the connections and make sure there is no shortcut before the power is turned on.

The procedure to measure characteristics of pressure head versus frequency is as follow:

- (1) Set the driving voltage to be 60 V.
- (2) Turn on voltage amplifier and signal generator. At each frequency, wait for a while until the meniscus positions in two tubes are stable, record the pressure head at different frequency.
- (3) Fix the driving voltage to be 150 V. Adjust frequency range. Wait for water/air interface is stable, and then record the pressure drop.
- (4) Plot the pressure head versus frequency curves. Find the peak working frequency.

The procedure to measure characteristics of pressure head versus voltage is:

- (1) Set the driving frequency at the peak working frequency.
- (2) Turn on voltage amplifier and signal generator. The input voltage to the PZT disk is adjusted from 0 to 150 V. At each voltage, wait for a while until the meniscus positions in two tubes are stable, record the pressure head at different voltage.
- (3) Plot the pressure head versus voltage curves.

Fig. 3.6 Experiment setup for pressure head measurement.

Fig. 3.7 Pressure measurement for (a) Pump without buffer; (b) Pump with buffers.

In the pressure head measurement, based on the uncertainties for ruler reading 0.25mm, the liquid meniscus position 0.25mm, the minimum pressure head 5mm, the maximum relative error is about 10%. All the experiments were repeatable.

Fig. 3.7 shows the pressure measurement for two pumps, the arrows in figures indicate clearly that there is pumping effect. Pumping direction is also illustrated in Fig. 3.7. It has been observed that the pumping direction for the pump without buffer is along the nozzle direction, as indicated by arrows in Fig. 3.7a. The pumping direction for pump with buffers is reversed as shown in Fig. 3.7b.

3.2.2.2 Flow rate measurement

To measure the maximum flow rate at zero back pressure, the glass capillaries were positioned horizontally. Fig. 3.8 depicts sketch and photograph of the experimental set up for flow rate measurement. With the known water/air interface meniscus position, the time and the capillary diameter, the flow rate was calculated from the velocity of the meniscus position at the pump outlet tube. The velocity was measured manually using a ruler and a stopwatch. Based on the uncertainties for ruler reading 0.5mm, the liquid meniscus position 0.5mm, the stop watch accuracy 0.01 second, and the liquid column length 20mm, the relative measurement error is about 2.5%.

Fig. 3.8 Schematics and photos of experiment set up for flow rate measurement.

The pumping flowrates are measured with the following preparatory procedure:

- (1) Inject the DI water into pump tube by using syringe. Avoid air bubble in pump chamber before fix the pump horizontally on table.
- (2) Accomplish the connections of signal generator, voltage amplifier, and actuator unit. Check the connections and make sure there is no shortcut before the power is turned on.

The procedure to measure characteristics of flow rate versus frequency is:

- (1) Set the driving voltage to be 60 V.
- (2) Turn on voltage amplifier and signal generator. At each frequency, record the distance of the meniscus position of water/air interface at the pump outlet tube and the time.

- (3) Set the driving voltage to be 150 V. Adjust the frequency range. Record the distance and the time.
- (4) Plot the flow rate versus frequency curves. Find the peak working frequency.

The procedure to measure characteristics of flow rate versus voltage is:

- (1) Set the driving frequency at the peak working frequency.
- (2) Turn on voltage amplifier and signal generator. The input voltage is adjusted from 0 to 150 V. At each voltage, record the distance of the meniscus position of water/air interface at the pump outlet tube and the time.
- (3) Plot the flow rate versus voltage curves.

3.2.2.3 Disk deflection measurement

From the pumping pressure head and flow rate measurement, both pump with buffers and pump without buffer have pumping effect (Pumping characteristics will be discussed in next section). Since the PZT disk as the actuator is a key component to operate micropumps, the dynamics of the PZT disk is examined, in order to further investigate the frequency characteristics of the pump.

A non-contact measurement system was used to detect PZT disk deflections and velocities. The non-contact measurement system consisted of a probe (5530, ADE Microsense II Active Probe Model, USA) and a module (5130, ADE Microsense II OEM Gaging Module, USA). The non-contact measurement system was calibrated by a micrometer (Oriel 14000, USA) to give the input displacement and the output voltage was read from an oscilloscope (TDS 210, Tektronix).

As shown in Fig. 3.9, to measure the disk deflection, the probe was positioned on the top of the piezoelectric disk (no contact). The probe was pointed to the disk center so that the results were corresponding to the disk deflections at the center. The module can control the distance between the probe and the PZT disk in an effective range by a display lamp. The transient disk deflection was captured by the probe and oscilloscope at various applied frequencies and voltages. The measurement was conducted with the DI water loaded inside the pump.

Fig. 3.9 Photograph of the measurement of disk deflection, (a) Micropump; (b) ADE Microsense II Probe; (c) ADE Microsense II OEM Gauging Module, which is used to control distance between the probe and the PZT disk in an effective range by too near or too far lamp.

3.2.3 Experimental Results and Discussions

3.2.3.1 Flow rate and Pressure head

As pointed out earlier, both pump with buffers and without buffer have pumping effect, and pumping directions are opposite each other. In this section, the experimental data of pumping flow rate and pressure head related to different frequency and voltage are used to illustrate the pumping characteristics for the two pumps respectively.

Fig. 3.10 shows the flow rate and pressure head versus frequency at a constant voltage of 60 V for the pump with buffers,. The experimental results show that the effective pumping occurs in the frequency range from 20 to 110 Hz. In the frequency range below 20 Hz and above 110 Hz, there is no pumping effect. At 70 Hz actuation, both flow rate and pressure head reach to their maximum values. The peak flow rate is about 0.075 mL/min and the peak pressure head is around 15 mmH₂O. By increasing the driving voltage to 150 V, as shown in Fig. 3.11, the effective pumping frequency is

extended to above 250 Hz. Although the peak working frequency is still at 70 Hz, the peak values for the flow rate and pressure head are higher than those at driving voltage of 60 V. The maximum flow rate is above 0.6 mL/min and the maximum pressure head is about 140 mmH₂O at the driving voltage of 150 V.

Fig. 3.10 Flow rate and pressure head versus frequency at voltage 60 V for the pump with buffers.

Fig. 3.11 Flow rate and pressure head versus frequency at voltage 150 V for the pump with buffers.

Fig. 3.12 Flow rate and pressure head versus frequency at frequency 70 Hz for the pump with buffers.

To investigate the effect of driving voltage, the characteristics of the flow rate and pressure head in term of voltage are plotted in Fig. 3.12 for the pump with buffers. The frequency is fixed at the optimum working frequency of 70 Hz. The actuation voltage is varied from 15 V to 165 V. From the curves in Fig. 3.12 we can see that the pumping effect is almost proportional to the input driving voltage.

The pump performance with various frequencies and voltages of drive signals are shown in Figs. 3.13 and 3.14 for the pump without buffer. At the actuation voltage 60 V, the pump generates a pressure head about 130 mmH₂O and flow rate about 0.4 mL/min around 70 Hz-80 Hz, which are much higher than that generated by the pump with buffers at the same voltage. In Fig. 3.14, the pressure head (the right axis) is plotted from 15 V up to 165 V at 70Hz for the pump without the buffer. The pressure head at 150 V is seen to reach to 150 mmH₂O.

Fig. 3.13 Flow rate and pressure head versus frequency at voltage 60 V for the pump without buffer.

Fig. 3.14 Flow rate versus voltage at frequency 70 Hz for the pump without buffer.

In general, it is seen that both pump with buffers and pump without buffer product maximum flow rate and pressure head around 70 Hz, and there are almost no pumping effect when the actuation frequencies are greater than 300 Hz or below 20 Hz. At fixed

frequency, pumping effect increases with voltage increases for both pumps. The pumping direction is opposite each other for the two pumps with/without buffers.

The maximum pumping pressure head and flow rate are around 140 mmH₂O and 0.6 mL/min under actuation voltage of 150 V for pump with buffers, which are relatively high for micropumps in general. The performance of the pump is comparable to the similar pumps [143] in term of flow rate. However, the working frequencies of the present pumps are much lower than most of micropumps which worked at frequencies in order of kilo Hz. The pumps with low operation frequency would have fewer disturbances to the operators, as human audio ability is more sensitive in frequency range 1-4 kHz and less sensitive at frequencies less than 100 Hz. Although the peak frequency is always around 70 Hz, the pumping performance is much weaker for the pump with buffers at inlet/outlet than that of the pump without buffer. At the actuation voltage of 60 V, the peak flow rate is only 0.075 mL/min and peak pressure head is around 15 mmH₂O for the pump with buffers, while at the same actuation conditions the pump without buffers produces the pressure head about 130 mmH₂O and flow rate about 0.4 mL/min.

3.2.3.2 Disk deflection and pumping flow rate

In order to further investigate low operation frequency features of the pumps, the dynamics of the piezoelectric disks are examined in order to see if the peak pumping performance is caused by the maximum deflection or maximum velocity of piezoelectric disk at the driving conditions.

The deflections and velocities of the piezoelectric disk used in the pumps are measured using a non-contact measurement system. The results are served for two purposes. One is to study the frequency characteristics of the pumping effects, and the other is to provide input data for the numerical simulations.

The experimental results of the disk deflections were obtained using the experimental setup discussed in the previous section 3.2.2.3. Figs. 3.15 and 3.16 show the amplitude of the disk deflection versus frequency and voltage for two pumps. It can be seen in Fig. 3.15 that the disk deflection decreases when the frequency increases, but increases

with the driving voltage increases. The maximum deflection is less than 50 μm at the lowest frequency. The deflection is almost unchanged at frequencies above 150 Hz. For the pump without the buffers, the disk deflection curves are similar to that of pump with the buffers and the results are shown in Fig. 3.16.

Fig. 3.15 Measurement results of the actuation disk for the pump with buffers. (a) Disk deflection versus frequency and (b) Disk deflection versus voltage.

Fig. 3.16 Measurement results of the actuation disk for the pump without buffers. (a) Disk deflection versus frequency and (b) Disk deflection versus voltage.

In order to analyze the effect of disk deflection and velocity on the pumping characteristics of the present pumps, the disk deflection and velocity, together with the pumping flow rate are normalized by their maximum values and are plotted in Figs. 3.17-3.20. Fig. 3.17 shows the flow rates, disk deflections and velocities relate to frequency from 10 to 120Hz at a constant driving voltage of 60 V for the pump with buffers. The peak flow rate occurs at frequency of 70 Hz, while the maximum disk deflection and velocity occur at frequency 10 Hz and 120 Hz, respectively. When the

driving voltage is increased to 150 V, the results are plotted in Fig. 3.18. The effective pumping frequency can reach to 200 Hz, at which the disk velocity reaches the maximum value of 0.1 m/s (not shown in Fig. 3.24). The solid squares represent the flow rate varying with the frequency. It is clearly seen from Figs. 3.17 and 3.18 that the peak pumping frequency is around 70 Hz in term of flow rate. However, at 70 Hz, both disk deflections and velocities are actually not at their maximum values. The maximum disk deflection occurred at the lowest frequency while the maximum disk velocity appeared at the highest frequency. The results indicate that the maximum pump effects are not produced by large amplitudes of the disk deflection or velocity at this frequency. In other words, the maximum pumping flow rate or pressure head is not controlled by the actuation strength but probably by the flow rectification mechanism associated with the frequencies. We believe that the acoustic resonance feature of the pump configuration probably attributes to the pump operation frequencies, and this will be further studied later by numerical simulations.

Fig. 3.17 Flow rate, disk deflection, and disk velocity versus frequency at voltage of 60 V for the pump with buffers.

Fig. 3.18 Flow rate, disk deflection, and disk velocity versus frequency at voltage of 150 V for the pump with buffers.

Fig. 3.19 Flow rate, disk deflection, and disk velocity versus frequency at voltage of 60 V for the pump without buffer.

For the pump without buffer, the situation is similar to the pump with buffers. The Flow rate, deflection and velocity of piezoelectric disk vary from different frequencies and voltages are plotted in Figs. 3.19 and 3.20, respectively.

Fig. 3.20 Flow rate, disk deflection, and disk velocity versus frequency at voltage of 150 V for the pump without buffer.

3.3 Numerical Simulations

Based on the measurements of pumping performance and piezoelectric disk dynamics presented in Section 3.2, it is concluded that the maximum pumping effects around 70Hz are not produced by large amplitudes of the piezoelectric disk deflection or velocity at this frequency. The pumping effects are probably controlled by the flow rectification mechanism, which is further studied by numerical simulation of the fluid field inside the pumping chamber.

The simulations in this section are carried out by using FLUENT for both pumps. The two dimensional model developed by Lu and Wu [30] is used in the present study, in which the disk actuations are converted into source terms in both continuity equation and momentum equation. The two dimensional model has advantages of saving computation time and much better convergence in simulation.

3.3.1 Problem Description and Assumptions

As depicted in Fig. 3.4, the valveless micropumps in the present study consist of a chamber with the diameter of 16 mm, a nozzle-shape channel with acoustically featured profile, and two straight channels with length of 10 mm and width of 1 mm. There are two buffers with length of 6 mm and width of 8 mm at the outlet and inlet in one micropump. The numerical simulation has been conducted for both pumps, with buffers and without buffer.

The numerical simulations in the present study are based on a two dimensional method developed by Lu and Wu [30], in which the following assumptions are used:

- (1) The ratio of the pump thickness to diameter of pump chamber is small, much less than 1. In our case, the pump thickness is 300 μm , the chamber diameter is 16 mm, and the ratio is 0.01875, which is small enough to use integral-averaged thickness method.
- (2) The ratio of the diaphragm amplitude to the pump thickness (channel depth) is small. From our experimental results, the maximum disk displacement amplitude is about 45 μm which is much less than the channel depth 300 μm .
- (3) The gravity force is neglected and there is no body force to be considered. The flow is viscous and incompressible laminar flow, which is supported at the small Reynolds number Re . Re is calculated by $Re = \frac{uh\rho}{\mu}$, where u is the maximum flow velocity in the chamber, h is the depth of the channel (300 μm), ρ and μ are the density and dynamic viscosity of the DI water. The maximum Re is found to be 350 in the present pumps.
- (4) The boundary conditions require the pressure to be zero (atmospheric pressure) at both inlet and outlet.

3.3.2 Governing Equations

The two dimensional method developed by Lu and Wu [30] is presented in this section. The governing equations for an unsteady, viscous and incompressible fluid flow originated from the momentum and continuity equations are expressed as follow:

$$\begin{aligned}\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} &= -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{V}, \\ \nabla \cdot \mathbf{V} &= 0,\end{aligned}\tag{3.2}$$

where $\mathbf{V}$ is fluid velocity in x , y , and z directions, t , ρ , p and ν are time, density, pressure, and kinematic viscosity, respectively.

The integral-averaged continuity equation is written as

$$\frac{\partial \zeta}{\partial t} + \nabla \cdot (h \bar{\mathbf{V}}) = 0,\tag{3.3}$$

where h is the pump thickness as a constant, ζ is the oscillation displacement of the piezoelectric disk. $\bar{\mathbf{V}}$ is the integral-averaged horizontal velocity in two-dimensional flow, expressed as

$$\bar{\mathbf{V}}(x, y) = \frac{1}{h} \int_0^h \mathbf{V}(x, y, z) dz.\tag{3.4}$$

The flow variation behavior in thickness of the horizontal flow is similar to a periodical flow between two infinite parallel planes [144], thus the local horizontal velocities can be expressed as

$$\mathbf{V}(x, y, z, t) = \bar{\mathbf{V}}(x, y, t) G(z, t),\tag{3.5}$$

where $G(z, t) = \frac{g(z, t)}{\bar{g}(t)}$, $g(z, t) = \text{Re} \left\{ \frac{1}{i\rho\omega} \left[1 - \frac{\cosh(\lambda(z - h/2))}{\cosh(\lambda h/2)} \right] e^{i\omega t} \right\}$, $\lambda = \sqrt{i\omega/\nu}$.

By setting the damping coefficient α and the non-linear coefficient β as

$$\begin{aligned}\alpha &= \frac{\nu}{h} \left[\frac{\partial G(z, t)}{\partial z} \right]_0^h, \\ \beta &= \frac{1}{h} \int_0^h G^2(z, t) dz,\end{aligned}\tag{3.6}$$

and integrating Eq. (3.2) over the pump thickness (z -direction), a two-dimensional momentum equation is obtained for the horizontal velocity $\bar{V}$ [30]:

$$\frac{\partial h\bar{V}}{\partial t} + \beta \nabla \cdot (h\bar{V}\bar{V}) = -\frac{h}{\rho} \nabla p + \nu h \nabla^2 \bar{V} + \alpha h \bar{V}. \quad (3.7)$$

The deflection of the disk is given by prescribed shapes, which is a function depending on (x, y, t) . Following the Timoshenko's theory [25], a prescribed profile for the deflection of a clamped circular plate with uniformly distributed load is:

$$\begin{aligned} \zeta(x, y, t) &= A(t) \left(1 - \left(\frac{r}{R} \right)^2 \right)^2, \\ A(t) &= A_0 \sin(2\pi f t), \end{aligned} \quad (3.8)$$

where $r = \sqrt{x^2 + y^2}$ is the distance from the centre, R is the radius of the circle in the pump chamber, f is the actuation frequency, and A_0 is the maximum deflection at the centre of the piezoelectric disk, which is experimental data from section 3.2.3.2.

Finally, the two-dimensional momentum equation (3.7) and continuity equation (3.3) are written respectively as

$$\frac{\partial \bar{V}}{\partial t} + \nabla \cdot (\bar{V}\bar{V}) = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \bar{V} + F_{\bar{V}}, \quad (3.9)$$

$$\nabla \cdot \bar{V} = -\frac{1}{h} \frac{\partial \zeta}{\partial t}, \quad (3.10)$$

where $F_{\bar{V}} = \alpha \bar{V} + (1 - \beta) \nabla \cdot (\bar{V}\bar{V}) - \frac{\partial \zeta}{\partial t} \frac{\bar{V}}{h}$.

Eqs. (3.9) and (3.10) are solved by FLUENT with user-defined-function (UDF) for the body force term and source term. In Eqs (3.9) and (3.10), α is a parameter proportional to the fluid viscosity, β is a parameter associated with the convection terms in the N - S equation. The detailed derivations and calculations for α and β are

described in Appendix A. In the simulations, the time averaged α and β are computed for each driving frequency.

In this simulation, the relevant boundary conditions are specified as: the pressure is zero (equal to atmospheric pressure, indicating that the pressure is a gauge pressure in all equations in the Chapter 3) in the inlet and outlet of micropump, and the displacement of the disk is given by Eq. (3.8).

3.3.3 Mesh Constructions and Independent Analysis

Fig. 3.21 Sketch of mesh constructions of (a) Pump with buffers; (b) Pump without buffer; (c) The junction between the chamber and channels in pumps; (d) The junction between the buffers and channels in the pump with buffers.

Two configurations of the micropump are simulated, as shown in Fig. 3.21a with buffers connected at both ends of channels and in Fig. 3.21b without buffers. The unstructured meshes were generated by the software Gambit. Fig. 3.21 shows the nonuniform meshes distribution sketch. The meshes are refined in the channels, the junctions between the chamber and channels (Fig. 3.21c) and the junctions between the buffers and channels (Fig. 3.21d). The mesh refinement is used to capture the detailed flow fields in these areas, while the simulation time is saved by using coarse mesh in the other areas to reduce the total mesh number.

There are three levels of meshes, based on the same mesh refinement method, in the mesh independent analysis with total mesh number 64532, 133840, 236460 elements, respectively. In Fig. 3.22, the pressure along the center line at $t = T/2$, frequency of 70 Hz, voltage of 60 V for the pump with buffers are plotted for three levels of meshes. It can be observed that mesh of 133840 elements satisfies the requirement of simulation, while mesh of 236460 elements requires longer calculated time for similar results. Mesh of 133840 elements was chosen in the numerical simulation. The three mesh levels are further tested in the flow rate calculations for the pump with buffers, and the results are shown in Fig. 3.23. The three curves confirm that the mesh level of 133840 can produce reasonably accurate results.

Fig. 3.22 Mesh independent analysis of the pressure on the center line at $t = T/2$ (T is the period), frequency 70 Hz, voltage 60 V for the pump with buffers.

Fig. 3.23 The flow rates for different levels of mesh for the case at frequency of 70 Hz and voltage of 60 V for the pump with buffers.

3.3.4 Simulation Results and Comparison with Experiments

3.3.4.1 Pumping direction and flow patterns

Numerical simulation was carried out using FLUENT software. Eqs. (3.9) and (3.10) were solved by the finite volume method to investigate the flow behaviors of micropumps. The body force term and source term were treated as UDF in FLUENT. The second order upwind algorithm in space and implicit iterative scheme in time were chosen in a two-dimensional double precision (2ddp) full simulation model.

Fig. 3.24 shows the transient flowrates, together with the average pumping flowrates, in one pumping cycle for the pumps with and without the buffers. Corresponding to the sinusoidal actuation, the fluid is sucked into the pumping chamber from both ends when the piezoelectric disk moves up and is pumped out from both ends while the disk moves down. If the sucking mode and pumping mode are precisely symmetric, there will be no net pumping flow. However, the simulation results plotted in Fig. 3.24 show that the average flowrate is -0.081 mL/min (the positive pumping direction is defined as from the end-A to end-B) for the pump with buffers and 0.259 mL/min for the pump without the buffers, indicating that there are pumping effects for both pumps and the pumping directions are opposite each other.

Fig. 3.24 The pumping flowrates in one pumping cycle for two pumps working at the driving frequency of 70 Hz and voltage of 60 V. (a) The pump with buffers and (b) The pump without buffer. T is the pumping period.

The numerical simulations provide the detailed information for the flow fields inside the pumps. Fig. 3.25 illustrates the transient flow streamline patterns in one period for the pump with buffers. The actuation is at frequency of 70 Hz and voltage of 60 V. The flow fields at four moments in one period T , $t = T/4$, $t = T/2$, $t = 3T/4$ and $t = T$ are plotted. At $t = 1/2T$, the disk diaphragm is at the mid-positions moving downwards to push the fluid out from the pump chambers, while at $t = T$, the disk diaphragm is at the mid-positions moving upwards to suck the fluid into the pump chambers. At these two moments, the flow streamlines inside the buffered pump are similar and symmetric though the fluid is flowing out at $t = 1/2T$ and flowing in at $t = T$. Furthermore, since the diaphragm displacement at these two moments reaches its minimum, the complex interactions among the actuation, fluid dynamics and inertia result in small corresponding fluid velocities, and thus no any vortex is observed. However, it is noted that the flow patterns at $t = 1/4T$ and $t = 3/4T$ are very different. Specifically, vortices are generated near the junctions of the chamber connecting to the straight channel. A closer examination of those vortices indicated by the dashed rectangles and plotted in Fig. 3.26, it is seen that the flow and vortex patterns at these two moments are different. It shows clearly that, at $t = 1/4T$, there are two big vortices accompanied by two small ones, while at $t = 3/4T$, there are only two big vortices. The different flow patterns and features are also observed for the pump without the buffers and results are plotted in Figs. 3.27 and 3.28. The unsymmetrical flow patterns in one pumping cycle, especially at $T/4$ and $3T/4$, generate the flow rectification and thus the net pumping effect. This is further verified by observing the flow patterns at the actuation frequency 500 Hz, which has no pumping effect based on both the simulations and experiment. Fig. 3.29 illustrates flow streamlines for this case in the same area inside the pump chamber at 8 moments in one period. The upper row in Fig. 3.29 shows the four moments corresponding to the pumping phase when the fluid is pumped out from the chamber, while the lower row shows the four moments corresponding to the sucking phase when the fluid is sucked into the chamber. It is seen that the flow patterns at the two pumping phases are very similar and symmetric except the flow directions. This explains why there is no flow rectification and thus no pumping effect in this case.

Fig. 3.25 Flow streamlines at frequency of 70 Hz and voltage of 60 V for pump with buffers (a) $t = T/4$ when the disk reaches to the up-most position; (b) $t = T/2$ when the disk moving down in the middle position; (c) $t = 3T/4$ when the disk reaches to the bottom-most position; (d) $t = T$ when the disk moving up in the middle position.

Fig. 3.26 (a) Detailed flow streamlines inside the dashed rectangular indicate in Fig. 3.25(a) at $t = T/4$, and (b) detailed flow streamlines inside the dashed rectangular indicate in Fig. 3.25(c) at $t = 3T/4$. The pump with buffers is actuated at 70Hz and 60V.

Fig. 3.27 Flow streamlines at frequency of 70 Hz and voltage of 60 V for the pump without buffers (a) $t = T/4$ when the disk reaches to the up-most position; (b) $t = T/2$ when the disk moving down in the middle position; (c) $t = 3T/4$ when the disk reaches to the bottom-most position; (d) $t = T$ when the disk moving up in the middle position.

Fig. 3.28 (a) Detailed flow streamlines inside the dashed rectangular indicate in Fig. 3.27(a) at $t = T/4$ and (b) detailed flow streamlines inside the dashed rectangular indicate in Fig. 3.27(c) at $t = 3T/4$. The pump without buffers is actuated at 70Hz and 60V.

Fig. 3.29 Detailed flow streamlines in numerical simulations inside dashed rectangular areas at $t = T/8$, $t = 2T/8$, $t = 3T/8$, $t = 4T/8$, $t = 5T/8$, $t = 6T/8$, $t = 7T/8$, $t = 8T/8$. The pump with buffers is driven at frequency of 500 Hz and voltage of 210 V. There is no pumping effect in this case according to experiments.

3.3.4.2 Comparisons between the simulations and experiments

The numerically simulated flowrates are compared with the experimental results with various driving frequencies and voltages. The results are plotted in Figs. 3.30 to 3.34. For the pump with buffers, the simulated flowrates, comparing with the measured values in term of frequency are described in Figs. 3.30 and 3.31, for the actuation voltage 60 V and 150 V respectively. General agreements between the simulations and experimental values are observed. At the peak frequency 70 Hz, Fig. 3.32 shows the flowrates versus voltage, for both experimental results and the simulated values. The numerical results match well with the experimental values, showing that the net flow rate increases linearly with the driving voltage.

Fig. 3.30 Experiment and simulation of flow rate versus frequency at voltage of 60 V for the pump with buffers. The experimental error is about 2.5%.

Fig. 3.31 Experiment and simulation of flow rate versus frequency at voltage of 150 V for the pump with buffers. The experimental error is about 2.5%.

Fig. 3.32 Experiment and simulation of flow rate versus frequency at frequency of 70 Hz for the pump with buffers. The experimental error is about 2.5%.

For the micropump without buffer, the flow rate characteristics based on frequency and voltage are plotted in Figs. 3.33 and 3.34. It can be seen from figures that the simulation flowrates do not agree well with the measured values, though the flowrates

are of the same order and similar frequency characteristics. This is probably because the un-buffered boundary conditions in this case at inlet and outlet are difficult to be set correctly in the simulation to match with the actual conditions in the experiment.

Fig. 3.33 Experiment and simulation of flow rate versus frequency at voltage of 60 V for the pump without buffer. The experimental error is about 2.5%.

Fig. 3.34 Experiment and simulation of flow rate versus frequency at frequency of 70 Hz for the pump without buffer. The experimental error is about 2.5%.

3.3.4.3 Effect of channel configuration

In order to investigate the effect of channels geometry on the pump performance, the pumps with different channel lengths were simulated. In this study, the length of the straight channels, L1 and L2 as described in Fig. 3.35, are varied and the flowrates are calculated. The results at 60 V driving are plotted in Figs. 3.35 and 3.36 at frequencies of 60 Hz, 70 Hz, 80 Hz, and 90Hz. The solid squares represent the simulation results of the actual geometry used in the experiments. The peak frequency is at 70 Hz, which agrees with experimental observation.

The first extended simulation case is to remove L2 channels at the right while keep L1 channels unchanged. The asterisk lines in Figs. 3.35 and 3.36 show that the flowrate is increased at low frequency range for the pump with buffer, but it is reduced for the pump without buffers. The second case is to remove L2 channels and reduced L1 channels from 10 mm to 5 mm, and the flow rates are shown by open circles in figures. It is seen that the flowrates in both pumps are higher than the original designs and the peak frequency are remained around 70 Hz. Finally, by further shortening the L1 channels to only 2 mm, the flowrates are plotted as triangles shown in Figs. 3.35 and 3.36. The pumping frequencies are shifted to high frequency ranges and the peak pumping frequency has been changed from 70 Hz to 80 Hz. Furthermore, the pumping direction is opposite to the original pumping direction.

Fig. 3.35 Variation of flow rates of different geometry micropumps with buffers.

Fig. 3.36 Variation of flow rates of different geometry micropumps without buffer.

3.4 PIV Measurements of Flow Patterns in the Micropump

The numerical simulations in the previous section have been used to analyze flow field in the valveless micropump. From simulation results, the unsymmetrical flow patterns in one pumping period generate the flow rectification and thus the net pumping in the working frequency range. Out of the pumping frequency, flow field is symmetric in one pumping cycle, there is no flow rectification and thus no pumping effect. The unsymmetrical flow patterns are significant and interesting, especially the vortex pattern in micropump with buffers. The details can be found in section 3.3. Although the numerical simulations on the flow fields corresponding to various moments in a pumping cycle can explain the flow rectification mechanism in the valveless pump, there is no direct observations on the chamber flow during the pumping cycles to support the flow rectification mechanism. It is always desirable to have a direction flow visualization of the pumping flow inside the pump chamber. The PIV study of the flow characteristics in the pump is conducted in the current section. Besides, the PIV technique which enables to obtain transient flow patterns at various moments in one pumping cycle in the present study may have applications to other periodic flow.

3.4.1 Experimental Setup

The experimental setup to measure the velocity fields in the pumping chamber by using PIV technique is shown in Figs. 3.37 and 3.38. The PIV system consists of three main components: an illumination system, a CCD camera and a control system. Particles with mean diameter 50 μm were used as the seeding particles. In order to obtain high quality signal with around 2-5 particles per interrogation spot, NIST traceable polymer microspheres (Diameter of $49.7\mu\text{m} \pm 0.7\mu\text{m}$, Duke Scientific) was diluted with degassed DI water to act as the working fluid, 2×10^5 particles per ml. Tween 20 (Fisher Scientific) was added at a volume ratio of 0.5% to the particle solutions for reducing the particle adhesions to the channel walls.

Fig. 3.37 Experimental setup of PIV measurement. The two-channel signal generator provided driving voltage and phase trigger signals to both voltage amplifier and laser, respectively. Micropump was fixed on a shelf and actuated by the voltage amplifier. The actions of laser and micropump were assigned synchronized by external triggered signal from a two-channel generator.

Fig. 3.38 Photograph of PIV experimental setup.

A 15Hz dual-head pulsed Nd:YAG laser (Gemini PIV 200-15, New Wave Research Inc., USA) was used to produce a light sheet illuminating the particles in the pumping chamber. The dynamics of the particles was captured at each light pulse by a synchronized camera (HiSense MkII, Dantec Dynamics) focusing from the bottom PMMA plate of the pump. The camera view field is indicated by zone I in Fig. 3.39.

The resolution of the CCD camera is 1344×1024 pixels with 12 bit grayscale. The recorded images were digitally transferred to a personal computer (PC) for further analysis. The corresponding software (DynamicsStudio, Dantec Dynamics) implemented in the PC can control and synchronize the actions related to illumination, record and analyze images.

Fig. 3.39 The measurement zone I and zone II indicated by the dashed rectangulars in the micropump with buffers.

The PIV image acquisition was externally triggered by Transistor-Transistor Logic (TTL) signals (as t_2 and t_3 shown in Fig. 3.40) output from a two-channel signal generator (AFG3000, Tektronix). The generator was also used to drive the micropump (The sinusoidal signal t_1 shown in Fig. 3.40) using the other channel. The pump signal was amplified to 60 V by an amplifier (790, PCB Piezotronics). Fig. 3.40 shows timing diagram of the PIV measurement (not to scale). When the external trigger t_3 starts, the first particle image is recorded under the first laser flash, and then the second images is captured under the second laser flash with a time interval about 500-1200 μs . The time interval is adjustable in software according to the instantaneous velocity magnitude. In the experiments, the time interval was 500 μs as the pumping frequency of 70 Hz; while the time interval was 1200 μs as the pumping frequency of 500 Hz. The two images were recorded and transferred to the PC as one recording. Due to the 15Hz maximum laser sample rate and image transfer time limitations of the PIV system, the measurements were difficult to conduct for high frequency. Taking advantage to the periodic nature of the flow field, the image recordings can be repeated for the same flow conditions. This was achieved by taking the external trigger period to be an integer multiplication of the pumping period (T), as nT ($n = 1, 2, \dots, N$) shown in Fig. 3.40. For example, the pump was driving at frequency of 70 Hz, n was chose as 40 cycles, the TTL signal period was therefore $nT = 40/70$ and the TTL signal

was 1.75 Hz. It meant that the second recording was generated after one TTL signal period (40 pumping periods).

In the conventional PIV technique, the laser pulses are synchronized with the camera frames only, since flow characteristics in steady flows do not need synchronize with any signals. In the present study, the PIV images of the flow field were obtained at different moment in one pumping cycle by synchronizing the laser pulses with the pumping signals. The laser pulses could be triggered at any moment in a pumping period, which was specified and controlled by a time delay T_d set by the signal generator. The trigger signal with the time delay T_d is illustrated in Fig. 3.40. In the present experimental study, the pumping cycle was divided into 8 moments, namely, $T/8$, $2T/8$, $3T/8$, $4T/8$, $5T/8$, $6T/8$, and $7T/8$ and T . For example, when continuous sinusoidal signal 70 Hz with 60 V was connected to the pump, the laser pulse and camera exposure were controlled by external TTL signal of 1.75 Hz without any time delay, two signal started at the same time, the PIV system was set to get recordings of flow fields at the moment of $t = T$. If time delay of 1.7875 ms ($T/8$) is introduced to the TTL signal, the PIV system was set to get recordings of flow field at the moment of $t = T/8$.

Fig. 3.40 Timing diagram of the PIV measurement (not to scale).

All recordings were analyzed using the cross-correlation method with interrogation areas of 32×32 pixels and overlapped by 50% of each of their sides. 80 valid

recordings were used to generate an averaged flow velocity vector field for each moment in the pumping cycle.

3.4.2 PIV Results and Comparison with Simulation Results

In order to have a better evaluation on the pumping flow patterns obtained from the PIV measurement, it is necessary to understand the pump operation mode in one cycle. Fig. 3.41 shows the eight moments in one pumping cycle and the corresponding piezoelectric disk positions. The pump was actuated at 70Hz and the period T is $1/70 = 0.0143$ s. The pump operation cycle consists of the pumping phase, in which the fluid is pumped out from the chamber, and the sucking phase, in which the fluid is sucked into the chamber. In the sinusoidal cycle shown in Fig. 3.41, the pumping phase starts at $2T/8$ when the disk reaches to the up-most position and then is moving down to the mid-position at $3T/8$. At $t = 4T/8$ the disk is in the mid-position and continuously moving down from the mid-position at $5T/8$ to pump the fluid out of the chamber. The sucking phase starts at $6T/8$ when the disk reaches to the bottom-most position and is moving up from the bottom through $7T/8$ and T till $T/8$ in next cycle.

Fig. 3.41 Pumping cycle and eight moments corresponding to the piezoelectric disk positions moving up and down. The pumping phase starts at $2T/8$ when the disk reaches to the up-most position and is then moving down to the mid-position at $3T/8$. At $t = 4T/8$ the disk is in the mid-position and continuously moving down from the mid-position at $5T/8$ to pump the fluid out of the chamber. The sucking phase (lower row) starts at $6T/8$ when the disk reaches to the bottom-most position and is moving up from the bottom through $7T/8$ and T till $T/8$ in next cycle.

Fig. 3.42 Flow velocity patterns inside the pump chamber (zone I indicated in Fig. 3.39) at eight moments in one pumping period T . The left column from $2T/8$ to $5T/8$ is the pumping phase, while the right column is the sucking phase. The pump was actuated at 70Hz and the period T is 0.0143 s.

Fig. 3.42 shows the transient flow velocity fields measured by the PIV system in the pump chamber. The flow velocity fields were taken from the zone I shown in Fig. 3.39 at 8 different moments in a pumping cycle. The left column in Fig. 3.42 is the pumping phase from $2T/8$ to $5T/8$ and the right column is the sucking phase. It can be seen that the flow patterns in the pumping mode and sucking mode are roughly symmetric except the flows near the outlet of the chamber. In order to view the details of the flow near the outlet of the chamber, the flow velocity fields are zoomed at zone II (indicated in Fig. 3.39) and the results are presented in Fig. 3.43. The upper row is the pumping phase and the lower row is the sucking phase. It can be seen clearly that the flow fields are quite different. For example, there are four small vortices near the outlet at $2T/8$ when the piezoelectric disk is at the up-most position, while there are only two vortices near the outlet at $6T/8$ when the disk is at the bottom-most position. In the sucking phase at T when the disk is at the mid-position moving upwards, there is a pair of vortices near the outlet, while there is no any vortex in the pumping mode at $4T/8$ when the disk is also at mid-position but moving down. The different flow patterns during the pumping phase and sucking phase indicates a net flow will be generated by the pump in one cycle. By comparing the detailed PIV flow fields shown in Fig. 3.43 with the simulation flow streamlines shown in Fig. 3.44, it is interesting to see a qualitative agreement between these results in terms of the flow patterns, especially those vortices at various moments and locations.

Fig. 3.43 Detailed PIV flow patterns (in zone II) corresponding to the flow velocity fields at 8 moments shown in Fig. 3.39. The upper row is the pumping phase and the lower row is the sucking phase. The pump was actuated at 70Hz and the period T is 0.0143 s.

Fig. 3.44 Numerical simulations of the flow streamlines inside zone II (indicated in Fig. 3.39). The upper row shows the pumping phase from $t = 2T/8$ to $5T/8$. The lower row shows the sucking phase starting from $6T/8$, through $7T/8$ and T , to $T/8$ in next cycle. The pump was actuated at 70Hz and the period T is 0.0143 s.

3.5 Summary

In this chapter, a new design of valveless micropump has been demonstrated. The pump has an acoustically featured pumping chamber which functions for both flow pumping and rectification. The pump has two versions, one is a valveless micropump with buffers at inlet and outlet, the other is of straight inlet and outlet without buffers. The pumping directions are opposite each other for the two versions. Both pumps have been studied using experimental characterizations and numerical simulations. The results have shown that the micropump can produce relatively high flowrates and pressure head, depending on the actuation frequencies and voltages. The maximum pumping effects occur around 70Hz for the two pumps. The low pumping frequency is caused by the acoustic resonance feature of the pumping system, not due to the large disk actuations at the peak frequency. The numerical simulations agree qualitatively with the experimental results and also provide the detailed flow streamlines in the pumping chamber. The flow rectification mechanism is found to be attributed to asymmetric flow patterns during one pumping cycle. Furthermore, the detailed flow patterns have also been investigated using the PIV measurements. The measured flow velocity fields agree qualitatively with the simulation results.

Chapter 4

Mixing Enhancement in Microchannels with Oscillating Bubbles

4.1 Introduction

In the previous chapter, we have demonstrated pumping effect of a new design of valveless micropump which can produce relatively high flowrates and pressure head with low operation frequency. In the pump experiments, we observed that there was no pumping effect at high frequency. However, there were bubbles generated and oscillated around chamber-channel at kilo Hz frequency range. Taking the advantage of the oscillating bubbles to enhance the mixing, a micromixer is designed and developed.

Studies on acoustically enhanced microfluidic mixing have been reported in the literature [104-108, 110, 113, 114]. Based on ultrasonic vibration produced by a PZT diaphragm, an ultrasonic micromixer was designed by Yang et al. [108]. The PZT diaphragm was excited by a 60 kHz square wave at 50 Vpp. The drawback was that the mixing effect was limited and there was a problem associated with temperature rise induced by high-frequency ultrasonic actuation. An acoustic micromixer was developed by relying on bubble oscillation to induce mixing with lower frequency and voltage [110]. However, foreign gas bubbles needed to be introduced and trapped on the mixer chamber wall. Due to small dimensions and low fluid velocity, mixing in microfluidic systems is usually poor. Therefore, new designs of micromixer that can be fabricated easily and driven with lower frequency are still an attractive research direction.

In this chapter, a novel technique for the micromixing is studied, which enhances mixing in a polymer based microfluidic structure by using acoustically induced gas bubbles. The micromixer is of the design by using the acoustically featured chamber being similar to the valveless pump presented in Chapter 3. Experiments are conducted to study the effect of actuation frequency on the mixing processes in both DI water and high viscous fluids.

4.2 Micromixer Design, Fabrication and Experimental Setup

4.2.1 Micromixer Design and Fabrication

Fig. 4.1 Schematic illustration of the acoustic micromixer. (a) Side view of the mixer configuration; (b) Top view of the mixer.

The micromixer was designed and fabricated using the lamination technology which was used in the previous valveless micropumps. The mixer consisted of a circular actuation chamber, a nozzle-shape channel connected with two inlets, and a straight channel with outlet. The entire configuration is of acoustic resonance features [142]. Fig. 4.1(a) depicts a side view of the microfluidic mixer that was constructed by two 2 mm thick PMMA layers sandwiched with a spacer made of a 300 μm thick dry adhesive layer (Adhesives Research, Inc., Arclad 8102 transfer adhesive). A CO_2 laser was used to cut the adhesive layer to form a Y-channel for introducing mixing liquids from two inlets and a chamber for acoustic actuation. The height of the actuation

chamber and the Y-channel is 300 μm , and other dimensions are indicated in Fig. 4.1b. As shown in Fig. 4.1b, the chamber structure consists of two parts, a circle chamber to accommodate a piezoelectric disk and an exponentially expanded nozzle. The same design of the chamber was used in the valveless micropump without buffer in chapter 3. The nozzle-shape channel with the acoustic resonator profile was detailed in Eq. (3.1) and Fig. 3.4. A Y-channel was used as inlets. A 10 mm long and 1 mm wide straight channel was connected from another end of the chamber to form the outlet of the mixer. A piezoelectric disk of 10 mm diameter (Model number BZ21C15NS, purchased from AL Goodwell Industries Ltd) attached to a 0.1 mm thick and 16 mm diameter brass sheet was assembled underneath the circular part of the chamber. The brass sheet was directly in contact with the mixing liquid in the chamber, while the nozzle was sandwiched between the two PMMA layers. Fig. 4.2 depicts the assembly concept of the micromixer. Fig. 4.3 shows the assembled micromixer.

Fig. 4.2 Stacked concept of the micromixer.

Fig. 4.3 Assembled micromixer.

4.2.2 Experimental Setup and Measurement

The experimental setup for the mixing performance is shown in Fig. 4.4. The mixing was conducted in DI water first. Degassed DI water was supplied to the inlet *A*, and fluorescent dye dissolved in DI water degassed was supplied to the inlet *B*. Two syringe pumps (Cole-Parmer, 74900-05) were used and the same flow rate was set for two streams of mixing liquids at 5 mL/h, respectively. The piezoelectric disk as actuator was driven by a signal generator (33120A, Hewlett Packard, USA) and an amplifier (790, PCB Piezotronics, USA), where a sinusoidal signal from the signal generator was amplified 30 times by the amplifier. A mercury lamp was used as the illumination source for the fluorescence measurement. Six different frequencies were applied including 0.5 kHz, 1.0 kHz, 1.5 kHz, 2.0 kHz, 5.0 kHz, and 10.0 kHz. The input voltage was fixed at 108 V. Disk deflections were measured at these frequencies. The intensity of the fluorescent dye was recorded using a CCD camera (DCR-DVD803E, SONY), and the results were used to assess the quality of the mixing processes in the microfluidic structure described above.

Fig. 4.4 Experiment setup of micromixer.

There are a few steps in the experiments:

- (1) Put one syringe with degassed DI water, the other syringe with fluorescent dye dissolved in DI water degassed on two syringe pumps. Connect syringes with micromixer with tubes.
- (2) Switch on syringe pumps to inject mixing fluids into the micromixer. Make sure the device free from bubbles.
- (3) Fix the micromixer on a solid shelf. Connect signal generator and voltage amplifier to the micromixer.
- (4) Set two syringe pumps at 5 mL/h. Wait for the interface of two fluids being stable. Turn on the Light emitting diode (LED) as light source. Cover CCD camera with a filter plate. Record the images of the fluids interface without actuation as the reference.
- (5) Turn on voltage amplifier and signal generator. At applied voltage 108 V and frequency including 0.5 kHz, 1.0 kHz, 1.5 kHz, 2.0 kHz, 5.0 kHz, and 10.0 kHz, record the experimental characteristics of micromixer. Make sure the chamber free from bubbles at the beginning of measurement of mixing effect at each frequency.

4.3 Mixing Enhancement in for DI Water

4.3.1 Experimental Observation on Mixing

When the piezoelectric disk was not actuated, there was almost no occurrence of mixing throughout the mixer. This can be seen from a clear interface between the two streams of liquids shown in Fig. 4.5. This should be expected because the characteristic Re is very low. The Re is calculated by

$$Re = \frac{uh\rho}{\mu} \quad (4.1)$$

where u is the characteristic velocity, 10 mm/s, h is the characteristic hydraulic diameter, 0.46 mm, ρ and μ are the density and dynamic viscosity of the DI water. Re is of order $O(1)$ in the present experiments, suggesting that the mixing in this laminar flow case is dominated by molecular diffusion only.

Fig. 4.5 Visualization of fluorescent dye in mixing experiment before powering on the piezoelectric disk.

Once the piezoelectric disk was actuated, an enhancement in the mixing was observed, as shown in Fig. 4.6 which depicts the effect of applied frequency ranging from 0.5 kHz to 10 kHz on the mixing in the present microfluidic structure. The experimental images used for assessing the mixing quality are taken from the region indicated by the dashed-line rectangle in Fig. 4.5. It can be observed from experimental results that, when the frequency was 0.5 kHz and above 5 kHz, the mixing was poor and dominated by molecular diffusion only due to the laminar flow. That suggests that the acoustically induced vibration does not make noticeable contribution to the

mixing in these conditions. However, significant mixing was occurred within a window of the frequencies ranging from 1 kHz to 5 kHz, in which the gas bubbles were generated. After the power that drove the piezoelectric disk was turned on, bubble(s) could be generated within 1-2 seconds. As indicated by the arrows in Fig. 4.6, higher frequency actuation shifted the occurrence of the bubble generation towards to the Y-channel side and the size of bubbles became smaller. At the high driving frequency of 5 kHz, several small bubbles were found to be trapped on the channel wall. Based on the recorded images, under corresponding frequencies of 1 kHz, 1.5 kHz, 2 kHz, and 5 kHz, the induced bubbles sizes are found to be about 0.71 mm, 0.47 mm, 0.35 mm, and 0.29 mm, respectively. Under present flow conditions, a strong interaction between the induced bubbles and the acoustic field existed in the fluid, and it appeared in a dynamically stable situation. The presence of the bubble(s) not only altered the flow path that could exhibit some geometry effect on mixing, but most importantly caused a churning motion of mixing liquids around the bubble due to the bubble oscillation resulted from the interaction between the applied acoustic field and the bubble. Vortex motion in the liquid was observed in the vicinity of the individual bubble, and thus the chaotic flow might occur, giving rise to dramatic increase in the mixing efficiency. At 5 kHz, although multi bubbles were observed, the interaction between the bubble and the flow field trended to be weak due to smaller bubble size, giving rise to a lower the mixing quality compared to that at 2 kHz. Interestingly, as shown in Fig. 4.7, when the power was switched off, the acoustically induced bubble(s) were still present in the channel, but the mixing enhancement phenomenon was disappeared, suggesting that a change of flow path due to the presence of bubble(s) had insignificant geometry effect on the mixing in this case.

Fig. 4.6 Visualization and intensity distribution of fluorescent dye in the mixer for various applied frequencies. The experimental images (left) used for assessing mixing quality are taken from the region indicated by the dashed-line rectangle in Fig. 4.5. Arrows show the location of acoustically induced gas bubbles. The fluorescent intensity distribution (right) are obtained by digitized the fluorescent images along the cross-section, a-a shown in Fig. 4.1(b).

Fig. 4.7 The actuation induced bubbles at 1 kHz applied frequency are still in the channel when the power is switched off, but the mixing enhancement phenomenon is disappeared.

4.3.2 Efficiency of Mixing

To quantitatively characterize the mixing quality, A MATLAB code is written to process the captured fluorescent images. It is assumed that for a certain point in an image, the fluorescent dye concentration is related to the image intensity I_i . For analyses, we choose a cross-section located in the nozzle channel (as indicated by the line *a-a* in Fig. 4.1(b)). The results of the normalized fluorescent intensity distributions along such cross-section are also displayed in Fig. 4.6 for each driving frequency. Uniform intensities along the cross-section indicate good mixing, as shown in Figs. 4.6(b)-4.6(e), while a abrupt change of the intensities along the cross-section indicate a poor mixing, as shown in Figs. 4.6(a) and 4.6(f). Furthermore, the mixing efficiency can be calculated according to the intensities by the following expression:

$$\sigma = 1 - \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N (\bar{I}_i - \bar{I}_\infty)^2}}{\sqrt{\frac{1}{N} \sum_{i=1}^N (\bar{I}_{0i} - \bar{I}_\infty)^2}} \quad (4.2)$$

where N represents the total number of points examined along the cross-section *a-a*, $\bar{I}_i$ is the normalized intensity at each point, $\bar{I}_{0i}$ is the normalized minimum intensity at each point without mixing taking place (e.g., value 0 or 1 in this study), and $\bar{I}_\infty$ is the normalized maximum intensity in complete mixing states (e.g., value 0.5 in this study).

Fig. 4.8 Variation of the mixing efficiency with applied frequency.

Fig. 4.8 shows the mixing efficiency versus applied frequency calculated from Eq. (4.2) using the MATLAB code. It is noted that when the frequency was below 1 kHz or above 5 kHz, the mixing was poor (indicated by the low mixing efficiency less than 10 %). Significant mixing was occurred within a window of the frequencies ranging from 1 kHz to 5 kHz; for instance, at the driving frequency of 1.5 kHz the mixing efficiency could reach as high as near 90%.

4.3.3 Effect of Disk Vibrations

Fig. 4.9 Vibrating velocity of the piezoelectric disk versus various applied frequency.

The occurrence of acoustically induced gas bubble(s) in the present microfluidic structure is interesting and important. To analyze the effect of the disk vibration on the mixing, the disk displacements were measured by a non-contact measurement system consisted of a probe model (5530, ADE Microsense II Active Probe Model, USA) and a module (5130, ADE Microsense II OEM Gaging Module, USA) under various applied frequencies (experimental setup and measurement were the same as described in section 3.2.2.3 used in the micropump experiments), and the vibration velocity of the piezoelectric disk versus the frequency is shown in Fig. 4.9. Under the experimental conditions, the sound wave length is related to the sound speed, c and the frequency, f and can be approximated as $\lambda = c / f = 0.15 \sim 3 \text{ m}$ which is much larger than the characteristic dimension of the micromixer. Hence the effect of acoustic field itself on the liquid flow structure is insignificant here. In view of the fact that the area ratio of the brass sheet to the cross-section of Y-channel is nearly about 1000, using the mass conservation under assumption of incompressible fluid, it is estimated that the piezoelectric disk induced liquid mean velocity in the narrow Y-channel will be about 40 - 100 m/s within the frequency range of 1.0 kHz – 5.0 kHz. With such high

induced vibrating velocity in the narrow Y-channel, the vibrating pressure likely could reach the cavitation threshold (i.e., the amount of negative pressure needed) [145]. In other words, gas bubble(s) can be generated in the narrow channel within this acoustic frequency range. Further increasing frequency can result in the suppression of the cavitation [146]. This might explain why no bubble generation was observed in the mixing device once the frequency was above 10 kHz. However, no theory is available for predicting the acoustic cavitation threshold in a microchannel structure because acoustic cavitation is a complex process [145]. The bubble generation in the present mixromixer will be studied and discussed in next chapter.

4.4 Mixing Enhancement for High Viscous Fluids

From a practical viewpoint, mixing devices may involve in fluids with high viscosity and relatively large flow rates to achieve a high mixing yield. However effective mixing for fluids with high viscosity at relatively high flow rates in nature poses much more difficult to achieve microfluidic mixing [57, 76]. As a further development from the mixing in DI water presented in Section 4.3, the bubble enhanced mixing is extended in this section to fluids with high viscosity at relatively high flow rate.

4.4.1 High Viscous Mixing Fluids and Experimental Preparation

DI water-glycerol solutions were used in the experiments as working fluids to study the performance of the mixer for high viscous fluids. The dynamic viscosity could be adjusted by changing the mass fraction of glycerol in DI-water. Table 4.1 lists the properties of nine different types of DI water-glycerol fluids used in experiment. The dynamic viscosities were measured by a rheometer (Göettfert Capillary Rheograph 6000) at temperature 25°C. The densities of DI water-glycerol solutions were also measured. The water vapor pressures for different solutions listed in Table 4.1 were taken from the results by Kirgintsev and Luk'Yanov (Kirgintsev et al., 1962). All DI water-glycerol solutions were degassed before using for the mixing experiment.

Table 4.1 Dynamic viscosity, density and water vapor pressure of DI water-glycerol mixtures at 25°C

Glycerol percent weight	Viscosity (mPa·s)	Density (kg/m ³)	Water vapor pressure (Pa)
0% (DI water)	0.89	998	3173
50%	5.69	1109.65	2568
67%	16.00	1150.97	2128
70%	20.99	1161.08	2012
75%	30.40	1179.44	1793
76%	35.70	1183.78	1747
77%	40.51	1187.10	1700
78%	44.75	1187.84	1649
80%	50.76	1202.94	1640

Fig. 4.10 A picture of the mixing device used in the study. The image shows that in the absence of generated bubbles before actuating the piezoelectric disk and no mixing in the fluid. DI water-glycerol solution supplied from inlet A and a DI water-glycerol solution with fluorescent dye supplied from inlet B. The cross line C-C is chosen to analyze the mixing efficiency.

The experimental setup is the same with previous mixing for DI water, as shown in Fig. 4.4 in section 4.2, except the mixing fluids. In this experiment, the degassed DI water-glycerol solution was supplied to the micromixer at inlet A, and the same DI water-glycerol solution with fluorescent dye was supplied to inlet B. As shown in Fig. 4.10, two syringe pumps (KD Scientific Inc., USA) were used and the same flow rate was set for the two streams of mixing liquids. The cross line C-C is chosen to analyze the mixing efficiency, the position is different from the cross line a-a in Fig 4.1 since most of mixings take place in the chamber rather in the narrow channel. The piezoelectric disk was driven by the external signal generator

(33120A, Hewlett Packard) and the amplifier (790, PCB Piezotronics) where a sinusoidal signal from the signal generator was amplified 30 times. The input voltage to the piezoelectric disk in all experiments was fixed at 108 V.

4.4.2 Mixing for High Viscous Fluids and Effects of Fluid Viscosity

In the study of the effects of fluid viscosity and actuation frequency on mixing performance, the flow rate at both inlets was fixed at 5 mL/h and the piezoelectric disk was actuated at different frequencies ranging from 0.5 kHz to 3.5 kHz for each type of the DI water-glycerol solution (as listed in Table 4.1). The mixing images were recorded using a CCD camera (DCR-DVD803E, SONY). The intensity of grayscale in the recorded images is proportional to the fluorescent dye concentration. To quantitatively characterize the mixing quality, the same MATLAB code mentioned in Section 4.3.2 are applied to process the recorded images. A cross line C-C (as indicated in Fig. 4.10) located near the outlet of the mixing chamber was chosen to analyze the mixing efficiency. The mixing efficiency was calculated using Eq. (4.2) in Section 4.3.2.

Fig. 4.11 Effect of the actuation frequency on mixing of a fluorescent dye in the DI water-glycerol solution with a viscosity of 5.69 mPa·s. The actuation frequency was varied from 0.5 kHz to 3.5 kHz. The applied voltage and the flowrates were 108 V and 10 mL/h respectively. Under certain frequencies shown in Figs. 4.11(c)-(e), there are visible bubbles indicated by arrows.

The Reynolds number Re was calculated by Eq. (4.1), where u is the averaged flow velocity at the straight channel of the mixer, h is the depth of the channel (300 μm), ρ and μ are the density and dynamic viscosity of the DI water-glycerol solution, respectively, as listed in Table 4.1. Among all the experiments for high viscous fluids, the maximum Re was 43.61, corresponding to the case of mixing in the pure DI-water solution with a flowrate 140 mL/h., therefore laminar flows would be expected in the mixer channels. Before the piezoelectric disk was actuated, the experimental image (as shown in Fig. 4.10) indicated that the two streams were separated throughout the mixer, suggesting a very poor mixing. However, once the piezoelectric disk was actuated, a significant improvement on the mixing was observed in the mixer. The effects of the actuation frequency on mixing patterns are shown in Fig. 4.11. The mixing fluid in Figure 4.11 was a DI water-glycerol solution with viscosity of 5.69 mPa·s which is 6.4 time higher than that of the pure DI-water. It is seen from Figure 4.11 that corresponding to the driving frequency varying from 0.5 kHz to 3.5 kHz, the mixing patterns exhibit very differently. At 0.5 kHz, there was almost no mixing between the two fluid streams, as indicated in Fig. 4.11(a). At 1 kHz shown by Fig. 4.11(b), gas bubbles were generated and were oscillating in the straight channel under the actuation of the piezoelectric disk, resulting in a great mixing enhancement. The resultant mixing pattern in terms of the fluorescent dye distribution and the location of the induced bubble, shown in Fig. 4.11b, is very similar to that of the mixing in the pure DI-water (as shown in Fig. 4.6). The presence of oscillating bubbles is the key attributed to such mixing enhancement. The complete mixing was achieved within 2-4 seconds. When the actuation frequency was increased to 2 kHz and 3 kHz, the oscillating bubbles became smaller and were relocated inside the mixing chamber, as shown in Figs. 4.11(c)-(f). The mixing enhancement was still observed, but became less effective. When the frequency was further increased to 3.5 kHz, the bubbles were completely disappeared from the mixer. As shown in Fig. 4.11e, the mixing at this frequency exhibited almost the same scenario as the case of without imposing any actuation of the piezoelectric disk.

Fig. 4.12 Variation of the mixing efficiency with applied frequency for two different DI water-glycerol solutions. Mixing Fluids are DI water-glycerol solutions with viscosities of 5.69 mPa·s and 44.75 mPa·s under driving voltage 108 V and the flow rate 10 mL/h.

The mixing performance was also characterized by using the mixing efficiency which was calculated from Eq. (4.2) based on the experimentally acquired fluorescent images. The experiments for the mixing performance were repeated for all solutions listed in Table 1. The mixing efficiencies versus actuation frequencies are presented in Fig. 4.12. It can be seen that for a solution with its viscosity of 5.69 mPa·s, the significant mixing occurs between 1 kHz and 2.5 kHz and the mixing efficiency can reach as high as 94%. The mixing efficiency for the DI water-glycerol solution with its viscosity of 44.75 mPa·s (50 times of pure DI-water) is also plotted in Fig. 4.12, which to our best knowledge is the highest viscosity of fluids used in microfluidic mixing experiments. It is seen that, for the fluid with such high viscosity, the mixing efficiency can still attain 78%, but the working frequency range is reduced to 1.5 kHz – 2 kHz. For the solutions with the viscosity above 44.75 mPa·s, no bubbles was generated and hence poor mixing were observed in the experiment under the entire range of the driving frequency.

Fig. 4.13 The experimentally observed effective working frequency range for achieving good mixing in the DI water-glycerol solutions with various viscosities

Fig. 4.14 Mixing patterns of DI water-glycerol solutions with viscosity of 5.69 mPa·s at driving frequencies of 1.5 kHz and 2.5 kHz (a and b). DI water solutions with viscosity of 44.75 mPa·s at driving frequencies of 1.5 kHz and 2.5 kHz (c and d).

Fig. 4.13 provides the experimentally observed effective working frequency range for achieving good mixing in the DI water-glycerol solutions with various viscosities. It is seen that the working frequency range is decreased as increasing the viscosity of solution. For the pure DI water, the mixing occurs from 1 kHz to 5 kHz. While for the solution with its viscosity of 44.75 mPa·s, the effective mixing frequency is reduced to a range between 1.5 kHz and 2 kHz. Fig. 4.14 shows the mixing patterns for two different DI-glycerol solutions with viscosities of 5.69

mPa·s and 44.75 mPa·s and at the two driving frequencies 1.5 kHz and 2.5 kHz respectively. It is noted that except for the poor mixing in the 44.75 mPa·s DI water-glycerol solution shown in Fig. 4.14(d), the good mixing were observed in other three cases shown in Figs. 4.14(a), 4.14(b), and 4.14(c). This suggests that under relatively high actuation frequencies the bubble oscillations become weak in high viscous fluids, leading to poor or no mixings.

4.4.3 Effects of the Flow Rate

Fig. 4.15 The mixing efficiencies for the DI water-glycerol solution with its viscosity of 5.69 mPa·s at different flow rates.

In the study of the flow rate effect, the driving frequency was fixed at 1.5 kHz and the 50% DI water-glycerol solution ($\mu = 5.69$ mPa·s) was used. The flow rate at both inlets was increased from 5 mL/h to 70 mL/h, with the total flowrate in the mixer from 10 mL/h to 140 mL/h. The results are plotted in Fig. 4.15 in terms of the mixing efficiency vs. flowrate. It shows that the mixing efficiency decreases with increasing the flow rate. At the flow rate of 10 mL/h ($Re = 0.54$), the mixing efficiency is 94% resulted from a strong bubble oscillation. When the flow rate is increased to 120 mL/h ($Re = 6.48$), the mixing efficiency is dropped below 50% and the bubbles become smaller. At the flowrate 140 mL/h, no bubbles are present

inside the chamber and the mixing becomes very poor, indicated by efficiency less than 10%.

4.5 Experiments of a Straight Channel Mixer: No Mixing and No Bubbles

In order to further check that the mixing enhancement and bubble generation in the mixer are related to acoustically featured chamber, a reference device was fabricated by replacing the acoustically featured chamber with a straight channel, as shown in Fig. 4.16. The experimental setup for the straight channel mixer is the same as the mixing experiments in Sections 4.2-4.4. The mixing experiments were conducted at the driving frequencies between 0.5 kHz and 3 kHz and the flow rates at 10 mL/h.

Fig. 4.16 A reference device with a straight channel. (a) Structure with straight channel and (b) experimental device. The cross line d-d is chosen to analyze the mixing efficiency.

Two kinds of working fluids were used in the experiments, one is DI water, the other is DI water glycerol solution with viscosity of 5.69 mPa·s. All working fluids were degassed before injection into device. Fig. 4.17 shows the experimental images for reference device with DI water. It is seen that there is no bubble generated in the straight channel before and after the actuation was switched on, and the interfaces between two flow streams are straight throughout the channel, illustrated by Figs. 4.17a – 4.17c. The mixing in the straight channel was also characterized by using the mixing efficiency which was calculated from Eq. (4.2) based on the experimentally acquired fluorescent images. The cross line d-d in Fig. 4.16 is chosen to analyze the mixing efficiency. The mixing efficiency results are presented in Fig. 4.18. It can be seen that for DI water, there is no significant mixing effect and the mixing efficiency less than 10%.

Fig. 4.17 Experimental images of the reference device with DI water. (a) The actuation was off. (b) The actuation was switched on at frequency 1.5 kHz. (c) The actuation was switched on at frequency 2 kHz. The applied voltage and the flowrates were 108 V and 10 mL/h respectively.

Fig. 4.18 Variation of the mixing efficiency with applied frequency for DI water in the straight channel under driving voltage 108 V and the flow rate 10 mL/h.

The DI water glycerol solution with a viscosity of 5.69 mPa·s was also tested in the straight channel mixer. The experimental images are shown in Fig. 4.19 and mixing performance results are presented in Fig. 4.20. The results are seen to be similar to the case for pure DI water, there is no bubble generated in the channel and no mixing enhancement.

The results conducted on the straight channel mixer, no bubbles and no mixing, shown in Figs. 4.17-4.20, confirm that mixing enhancement with oscillating bubbles can only be achieved in the micromixer with the acoustic feature chamber presented in Fig. 4.1. The bubbles are indeed generated inside the fluid by the actuation, not by other mechanisms, such as due to the gas dissolved in the fluid or from the channel materials.

Fig. 4.19 Experimental images of the straight channel reference device for DI water-glycerol solution with a viscosity of 5.69 mPa·s. (a) The actuation was off. (b) The actuation was switched on at frequency 1.5 kHz. (c) The actuation was switched on at frequency 2 kHz. The applied voltage and the flowrates were 108 V and 10 mL/h respectively.

Fig. 4.20 Variation of the mixing efficiency with applied frequency for DI water-glycerol solution with viscosity of 5.69 mPa·s under driving voltage 108 V and the flowrate 10 mL/h.

4.6 Summary

In this chapter, a micromixer has been developed to achieve fast and effective mixing based on oscillating bubbles. The micromixer has the design with the actuation chamber being similar to the valveless micropump in chapter 3. Experiments have been carried out to examine the mixing performance. The results, based on the mixing efficiency calculated from experimentally acquired fluorescent images, have shown that good mixing can occur for both pure DI water and DI water-glycerol solution with high viscosity. For the pure DI water as the working fluid, when the mixer is actuated in the frequency range from 1.0 kHz to 5.0 kHz, bubbles can be generated in the channel near the actuation chamber. The interaction between the bubbles and unsteady flow under the actuation causes strong bubble oscillations leading to a significant mixing enhancement, in which the mixing efficiency could reach to 80%. For the high viscous fluids as the working fluids with high flowrates, the mixer still can achieve fast and effective mixing with a narrow working frequency range between 1.5 kHz and 2 kHz. The experiments have shown that good mixing with efficiency 78% can occur in the DI water-glycerol solution with a viscosity up to 44.75 mPa·s, which to our best knowledge is the highest viscosity of fluids in microfluidic mixing experiments. Furthermore, a reference device with a straight channel to replace the acoustically featured chamber has been tested under the same experimental conditions. It is observed that there is no bubble generated in the channel and no significant mixing occurred in the micromixer with the straight channel, which confirms that the bubbles are indeed generated inside the fluid by the actuation.

Chapter 5

Bubble Generation in the Microfluidic Chamber

5.1 Introduction

In Chapter 4, the enhancement of mixing by using actuation-induced bubbles has been presented. The formation of bubbles in the bubble-based mixer is an interesting feature and its mechanism needs to be understood. To achieve a better understanding of the micromixing using induced bubbles, it is important to investigate the bubbles in the channel, including how and where the bubbles are generated. As an extension to the previous work on actuation-induced bubbles for the mixing enhancement, the bubble generation is investigated in this chapter by both numerical simulation and experimental observation in the microfluidic channel. The numerical simulation, which is a two-dimensional model similar to what has been described in Chapter 3 for the micropump, is conducted to analyze the bubble generation and predict the location of bubbles. The experiments are carried out using a high speed camera to observe bubble generation and verify the simulation results.

5.2 Numerical Simulation of Pressure Distribution in

Micromixer

The mixing experiments presented in Chapter show that the bubbles in the micromixer occur only in a frequency range from 1 kHz to 5 kHz, depending on the fluid viscosities. It is possible to utilize a numerical model to explain why the bubbles are generated under such frequency range and to estimate the location of bubble generations. The simulations are based on a two-dimensional model used in numerical simulations of micropumps in chapter 3 and are focused on the pressure distributions in the fluids under the actuation. In the model, the piezoelectric disk actuations are

converted into the source terms in both the continuity equation and the Navier-Stokes (N-S) equation, which are written as Eqs. 3.9 and 3.10 in Chapter 3, are represented here,

$$\frac{\partial \bar{V}}{\partial t} + \nabla \cdot (\bar{V}\bar{V}) = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \bar{V} + F_{\bar{V}}, \quad (3.9)$$

$$\nabla \cdot \bar{V} = -\frac{1}{h} \frac{\partial \zeta}{\partial t}, \quad (3.10)$$

where $F_{\bar{V}} = \alpha \bar{V} + (1 - \beta) \nabla \cdot (\bar{V}\bar{V}) - \frac{\partial \zeta}{\partial t} \frac{\bar{V}}{h}$. V is the fluid velocity in x - y plane, p is the absolute hydraulic pressure, α is a parameter proportional to the fluid viscosity, β is a parameter associated the convection terms in the N-S equation. The definitions of α and β are given by Eq. (3.6) in Chapter 3. $\zeta(x, y, t)$ is a function representing for the actuation displacement on the upper surface, and h is the channel height. The parameters α and β depend on the fluid properties and actuation frequencies and their calculations are given in Appendix A. Eqs. 3.9 and 3.10 were solved by using the FLUENT software based on the finite volume method. The experimentally measured disk deflections at various driving frequencies were input into the model as the source terms. The flowrates are specified at the two inlets and the outlet of the mixer.

5.2.1 Numerical Results for DI Water

It is known that the bubbles may be generated in a fluid if the local pressure is lower than the vapour pressure of the fluid. The numerical simulation for the bubble generation study is to compute the fluid pressure distributions corresponding to the actuations so as to identify the possible regions in the mixer where the pressure is below the water vapour pressure, leading to the bubble generation. The transient pressure distributions are plotted in Figure 5.1. As illustrated in Fig. 5.1, the simulation results show, during the actuation, that there are low pressure regions in the microchannel under the driving frequency range of 1-5 kHz, where the water pressures fall below the water vapor pressure at temperature 25 °C, which is 3173 listed in Table 4.1. Outside this actuation frequency range, such as at 0.5 kHz or 6 kHz, the pressures in the channel are always higher than the water vapor pressure. The numerical results

indicate that bubbles can be generated in these low pressure regions under the driving frequencies of at 1-5 kHz. By comparing the simulation results with the experimental images (Fig. 4.6 in Chapter 4), it is seen that the low pressure regions in the simulations are not exactly the locations of oscillating bubbles shown in experiments. It is assumed that the low pressure regions are the locations of bubble generation, and the bubbles probably grow, move, collide and coalesce along the channel afterwards. To capture the location of bubble generation and bubble movements, the experiment is carried out by utilizing a high speed camera, and results are presented in Section 5.3.

Fig. 5.1 The computed transient pressure distributions for the DI water at different actuation frequencies. (a) 0.5 kHz, $t = 0.725T$ (T is the period of the driving voltage), the lowest pressure is 71810 Pa; (b) 1 kHz, $t = 0.643T$, the lowest pressure is 2990 Pa; (c) 1.5 kHz, $t = 0.557T$, the lowest pressure is 380 Pa; (d) 2 kHz, $t = 0.535T$, the lowest pressure 1290 Pa; (e) 5 kHz, $t = 0.5078T$, the lowest pressure is 3000 Pa; and (f) 6 kHz, $t = 0.725T$, the lowest pressure is 7600 Pa. The DI water vapor pressure at 25 °C is 3173 Pa. The flowrate through the mixer is 10 mL/h.

5.2.2 Numerical Results for High Viscous Fluids

It has been demonstrated by the experiments in Chapter 4 that the bubbles are generated inside the micromixer by the actuation in a frequency range, depending on the fluid viscosity and flowrate. The numerical simulation is therefore also conducted to investigate the bubble generation in the high viscous fluids.

Fig. 5.2 shows the transient pressure distributions for three different mixing fluids (pure DI-water, 50% DI water-glycerol and 78% DI water-glycerol solutions) at the driving frequency 1.5 kHz and flowrate 10 mL/h. It is seen that there exists low pressure regions inside the mixer chamber where the minimum pressures are lower than the corresponding water vapor pressures. The presence of such low pressure regiond suggests that bubbles can be generated from these regions. The effect of the driving frequency on the low pressure regions is examined by calculating minimal pressures for the 78% DI water-glycerol (with the highest viscosity $\mu = 44.75 \text{ mPa}\cdot\text{s}$ among testes fluids in this study, shown in Table 4.1) at a flowrate of 10 mL/h. The results are presented in Fig. 5.3 by plotting the ratio of the fluid pressure to the water vapor pressure versus the actuation frequency. It shows that there is a frequency window between 1.5 kHz and 2.2 kHz, in which the minimal pressures are less than the water vapor pressure. This frequency window agrees with the experimental observations presented in Chapter 4.

Fig. 5.2 The absolute pressure distribution at $t = 0.75T$ (T is the period of the driving voltage) under the actuation frequency 1.5 kHz for DI water-glycerol solutions with various viscosities. (a) $\mu = 0.89$ mPa·s, DI water without glycerol, the minimal pressure in the channel is 380 Pa, below the water vapor pressure 3173 Pa (Table 4.1); (b) $\mu = 5.69$ mPa·s, the minimal pressure in the channel is 580 Pa, below the water vapor pressure 2568 Pa; (c) $\mu = 44.75$ mPa·s, the minimal pressure in the channel is 1020 Pa, below the water vapor pressure 1649 Pa.

Fig. 5.3 The minimal pressure in the low pressure region at various driving frequencies. The working fluid is the DI water-glycerol solution with viscosity of 44.75 mPa·s. The water vapor pressure under 25 °C is 1649 Pa. The dashed line represents the water vapor pressure (or $P/P_{\text{water-vapor}} = 1$), below which the bubbles can be generated.

The effects of flowrate on the low pressure region were also studied in the 50% DI water-glycerol solution of viscosity 5.69 mPa·s under a fixed driving frequency of 1.5 kHz, while the flowrate was varied from 10 mL/h to 140 mL/h. The results are plotted in Fig. 5.4 with the minimal pressure inside the mixer. The simulation results show that the minimum pressures are always lower than the water vapor pressure if the flowrate is less than 120 mL/h, and hence the bubbles can be generated. When the flowrate is larger than 120 mL/h, the minimal pressures are higher than the water vapor pressure, suggesting that the bubbles will not be produced, and thus the mixing enhancement will not be occurred. These simulation results agree with the experimental measurements plotted in Fig. 4.15 (Chapter 4).

Fig. 5.4 The minimal pressure in the low pressure region at various flowrates. The working fluid is a DI water-glycerol solution with its viscosity of 5.69 mPa·s and the water vapor pressure is 2568 Pa. The dashed line indicates the water vapor pressure (or $P/P_{\text{water-vapor}} = 1$), below which the bubbles can be generated.

It is noticed that the low pressure regions obtained from the numerical simulations (plotted in Figure 5.2) are not exactly the same as the locations of the oscillating bubbles observed in our experiments. The situation is similar to the case in pure DI water. The low pressure regions are the locations of generating initial bubbles, and afterwards the bubbles may grow, move, collide and coalesce along the chamber channel. The dynamic process of the bubbles is verified by using a high speed camera and the results are presented in next section.

5.3 Bubble Generation Observation

5.3.1 Experimental Setup

The experimental setup to observe the bubble generation is shown in Fig. 5.5. The degassed DI water was supplied to two inlets of the micromixer. A high speed camera (FASTCAM 1024PCI, Photron) was used to record the bubble generation. The camera could capture up to 100,000 frames per second, and had high resolution up to 1024×1024 pixels at 3000 frames per second. The high speed camera was attached to a microscope (Nikon EclipseTE 2000-s, Japan) to capture the images.

From previously recorded mixing experimental images (Fig. 4.6 in Chapter 4), it can be estimated that the bubble is approximately at its maximum size in the driving frequency of 1.0 kHz. To optimize the visibility of the bubbles, the driving frequency for observing bubble generation was set at 1.0 kHz.

Fig. 5.5 Experimental setup for observing bubble generation by using a high speed camera.

5.3.2 Experimental Results and Discussion

Typical photos of bubble generation and movements are shown in Fig. 5.6. The zones, indicated as a dashed rectangular in Fig. 5.6a, were used to observe the bubble generation and moving. The raw image of the rectangular zone 1 (Fig. 5.6b) shows that the bubble are absent on without th actuation. The edge of the piezoelectric disk is not smooth due to the epoxy used to fix the disk. After the power of actuation is turned on, the raw image of bubble generation at $t = 0.02\text{s}$ is shown in Fig. 5.6c, the bubbles appear as dark spots because the images were reversed. It was observed in the experiments that the bubbles were flowing rightwards along the channel after generated. At $t = 0.6\text{s}$ the bubbles grew and moved out of the region zone 1 of the view shown in Fig. 5.6a. A larger field of view indicated as a dashed rectangular zone 2 in Fig. 5.6a is used to follow bubbles movement. Fig. 5.6d shows that the bubbles in the narrow channel are bigger than initial bubbles in Fig. 5.6c. As time elapsed, the bubbles continued to move and collide to form larger bubbles. Figs. 5.6e and 5.6f show the collision and coalescence of large bubbles at $t = 1.5\text{s}$, which enhanced mixing significantly as shown in mixing experimental images in chapter 4.

Fig. 5.6 Different stages of the bubbles generation processes in the mixing channel, working fluid is degassed DI water and driving frequency is 1.0 kHz. (a) Top view of the mixer, zones 1, 2 and 3 are observation zones. (b) The raw image of zone 1 before switching on the actuation. There are no bubbles. (c) The image of zone 1, 0.02 second after switching on the actuation. Some the initial bubbles occur. Camera setting: 10000 frames per second, 512×512 pixels, 3.5mm×3.5mm. (d) The image of zone 2, 0.6 second after switching on the actuation. The bubbles moving from zone 1 become bigger. Camera setting: 3000 frames per second, 1024×1024 pixels, 7.0mm×7.0mm. (e) and (f) The images of zone 3, 1.5 second after switching on the actuation. The collision and coalescence of bubbles are observed. Camera setting: 20000 frames per second, 512×256 pixels, 3.5mm×1.75mm.

All afore-described phenomenon observed in the experiment are repeatable. The spots of initial bubbles generated may not be exactly the same in different runs of measurement, however, they are all covered by the low pressure regions predicted in the numerical simulations.

5.4 Summary

The bubble generation mechanisms have been studied by carrying out numerical simulations to obtain pressure distributions inside the mixer. For both pure DI water and DI water-glycerol solutions with higher viscosity, the simulation results have shown that there is a low pressure region in the mixer, where the minimal pressures are lower than the corresponding water vapor pressure, so that the bubbles can be generated. The simulation results on the formation of the low pressure region for the bubble generation agree with the experimental observations in terms of the actuation frequency window, flow rate and fluid viscosity. The bubble generations are observed experimentally by using a high speed camera. It has been found that the bubbles, which are initially very small after being generated, move and grow along the channel, and finally form big bubbles in the channel. The simulations and observations confirm that the bubbles are generated in the micromixer by the actuation in the acoustically featured chamber.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

Two basic functions of microfluidic devices, pumping and mixing, have been investigated and presented in this thesis. The micropumps and micromixers are designed and developed. The pumps and mixers have similar but unique microfluidic chamber configurations which are of acoustic resonator features. Both experimental characterization and numerical simulations have been conducted. Following are main conclusions drawn from this study.

- (1) Two new designs of valveless micropumps have been developed: one is a pump with buffers at inlet/outlet and the other is of straight inlet/outlet without buffers. These two types of pumps have an acoustically featured pumping chamber which functions for both flow pumping and rectification. The pumping directions are opposite each other for the two types of pumps. The pumps can produce relatively high flowrates and pressure heads, depending on the actuation frequency and voltage. The maximum pumping effects are found to occur around 70 Hz, which is much low than kilo Hz reported in other micropumps. The low pumping frequency is caused by the acoustic resonance feature of the pumping design, instead of the large disk actuations at this frequency. The simple design and low operation frequency make the pump suitable for microfluidic integrations.
- (2) Numerical simulations, based on a simplified two-dimensional model, have been carried out to investigate pump performance and the transient flow field inside the pump chamber. The simulation results agree qualitatively with the experimental measurement in terms of pumping directions and pumping frequency characteristics. The simulations also provide the detailed flow streamlines in the pumping chamber over one pumping cycle. The flow rectification mechanism is

found to be attributed to asymmetric flow patterns during one pumping cycle. This is verified by using the PIV measurements of the flow velocity field in the pumping chamber. The measured flow velocity fields qualitatively agree with the simulation results.

- (3) The mixing enhancement has been achieved in the present micromixer due to oscillating bubbles generated in the microchannel by the actuation. Experiments have been carried out to examining the mixing performance. The results, based on the mixing efficiency calculated from experimentally acquired fluorescent images, show that good mixings can occur for both pure DI water and DI water-glycerol solutions with high viscosities. For the pure DI water used as the working fluid, the mixer works in the frequencies ranging from 1.0 kHz to 5.0 kHz, in which the bubbles are generated in the channel near the actuation chamber. The interaction between the bubbles and flow under the actuation causes strong bubble oscillations and thus leads to significant mixing enhancement with the mixing efficiency up to 80%.
- (4) For high viscous fluids used as the working fluids, the micromixer developed in the present study can also produce fast and effective mixings, but the working frequency range is reduced between 1.5 kHz and 2 kHz. The experiments have demonstrated that good mixing with efficiency 78% can be achieved in the DI water-glycerol solution with a viscosity up to 44.75 mPa·s, which to our best knowledge is the highest viscosity of fluids in microfluidic mixing experiments.
- (5) The bubble generation mechanisms in micromixer have been studied by both numerical simulations and direct observations using a high speed camera. For both pure DI water and DI water-glycerol solutions with higher viscosities, the simulation results shown that, under the actuation frequencies, there are low pressure regions in the mixer chamber, where the minimal pressures are lower than the corresponding water saturation vapor pressures, so that the bubbles can be generated. The images obtained from the high speed camera show that the bubbles, which are initially very small after being generated, move and grow along the channel, and finally form big bubbles in the channel. Both the simulations and observations confirm that the bubbles are indeed generated in the acoustically featured chamber by the actuations.

6.2 Recommendations for Future Work

Some microfluidic phenomena have been observed during the research on the micropumping and micromixing presented in the previous chapters. These phenomena are probably beyond the framework of the present study, but they are worthwhile to be studied further for both academic interests and practical applications. The following are two recommendations for further studies.

- (1) Since the micropump and micromixer developed in the present study have the similar chamber-channel configurations, it would be useful to develop an integrated microfluidic device which can function for both pumping and mixing by operating at different actuation frequencies.
- (2) Bubbles have been observed in the micromixer with the actuations at proper frequencies. The bubble dynamics inside the microchannels needs to be further studied, including bubble generation, growth, coalescence, migration and interaction with the fluid flows under the actuation.

Appendix A

A.1 Damping Coefficient α and Non-linear Coefficient β

The numerical simulations have been conducted for the fluid flows under the actuation in both micropumps and micromixers. The simulations are based on a two-dimensional model developed by Lu and Wu [30, 147]. The damping coefficient α and the non-linear coefficient β in this model are defined in Eq. (3.6) in Chapter 3 and are listed below,

$$\begin{aligned}\alpha &= \frac{\nu}{h} \left[\frac{\partial G(z, t)}{\partial z} \right]_0^h, \\ \beta &= \frac{1}{h} \int_0^h G^2(z, t) dz.\end{aligned}\tag{3.6}$$

In Eq. (3.6), $G(z, t) = \frac{g(z, t)}{\bar{g}(t)}$, where $g(z, t)$ is expressed as

$$\begin{aligned}g(z, t) &= \text{Re} \left\{ \frac{1}{i\rho\omega} \left[1 - \frac{\cosh(\lambda(z - h/2))}{\cosh(\lambda h/2)} \right] e^{i\omega t} \right\} \\ &= \frac{1}{\rho\omega E_c} [(E_c - C_c) \sin(\omega t) - D_c \cos(\omega t)],\end{aligned}\tag{A.1}$$

$$\text{and } \bar{g}(t) = \frac{1}{h} \int_0^h g(z, t) dz.\tag{A.2}$$

In Eq. (A.1),

$$C_c = \cos A_c \cosh A_c \cos B_c \cosh B_c + \sin A_c \sinh A_c \sin B_c \sinh B_c,$$

$$D_c = \sin A_c \sinh A_c \cos B_c \cosh B_c - \cos A_c \cosh A_c \sin B_c \sinh B_c,$$

$$E_c = (\cos B_c \cosh B_c)^2 + (\sin B_c \sinh B_c)^2,$$

$$A_c = \frac{\sqrt{2}}{2} \sqrt{\frac{\omega}{\nu}} \left(z - \frac{h}{2} \right), \text{ and } B_c = \frac{\sqrt{2}}{2} \sqrt{\frac{\omega}{\nu}} \frac{h}{2}, \quad \omega = 2\pi f, \quad f \text{ is the actuation frequency.}$$

Since the micropumps and micromixers are periodically driven at a given operation frequency, the time-averaged values for α and β are used in the simulations [147]:

$$\bar{\alpha} = \frac{1}{T} \int_0^T \alpha(t) dt, \quad (\text{A.3})$$

$$\bar{\beta} = \frac{1}{T} \int_0^T \beta(t) dt, \quad (\text{A.4})$$

where $T = 1/f$ is the period and f is the actuation frequency. In the simulations, the parameter α and β are calculated according to Eqs (3.6) and (A.1-A.4), depending on the fluid properties and actuation frequencies.

A.2 Temperature of PZT Disk in the Experiments

The experimental setup to measure the temperature generated by PZT disk is shown in Fig. A.1. The micropump setup is the same as that described in section 3.2.2. The micromixer setup is the same as Fig. 4.4 in section 4.2.2. An infrared camera (NEC thermo tracer TH9100WL, Japan) was used to record the temperature of the PZT disk, associated with the actuations.

Fig. A. 1 Experimental setup for temperature measurement using an infrared camera.

(a)

(b)

Fig. A. 2 Temperature measurement at $t = 2$ s after switching on the micropump and micromixer.
(a) The micropump at frequency of 70 Hz; **(b)** the micromixer at frequency of 2 kHz.

Fig. A. 3 Temperature measurement at $t = 30$ seconds after witching on the actuation of micropump at frequency of 70 Hz.

Fig. A. 4 Temperature measurement at $t = 15$ seconds after witching on the actuation of micromixer at frequency of 2 kHz.

The pump was actuated at frequency of 70 Hz and voltage of 60 V. The mixer was actuated at frequency of 2 kHz and voltage of 108 V. As shown in Fig. A.2, when the micropump and micromixer are actuated with 2 seconds, the temperature of the PZTs are still in room temperature. At 30 seconds after switching on the actuation, the

temperature generated by the PZT of the micropump is increased to 40 °C, as shown in Fig. A.3. While at 15 second after switching on the actuation in the mixromixer, the temperature at the PZT is above 70 °C, as shown in Fig. A.4.

The experiments on the micromixer in Chapter 4 showed that the bubbles were generated almost instantly after switching on the actuation, and within 2 seconds, the PZT disk and the fluid are still remained at room temperature. Therefore, the simulations in Chapters 4 and 5 were based on room temperature and results should be acceptable for comparing with the experimental observations for the bubble generation in the micromixer.

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